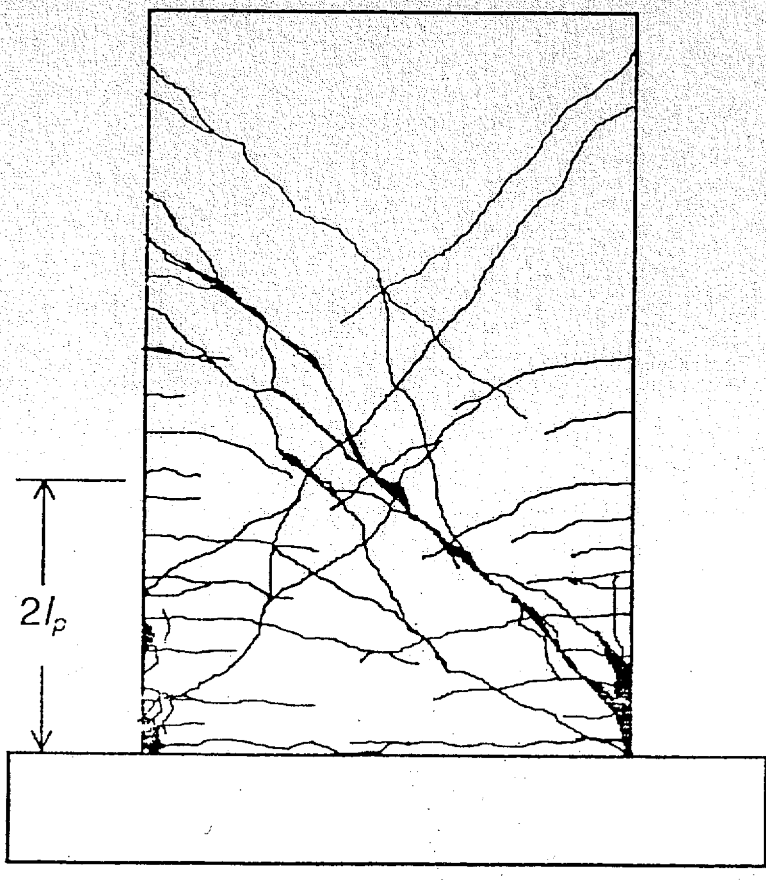
Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings

Basic Procedures Manual



FEMA 306

EVALUATION OF EARTHQUAKE DAMAGED CONCRETE AND MASONRY WALL BUILDINGS

Basic Procedures Manual

Prepared by:

ATC

Applied Technology Council (ATC-43 Project)

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The Partnership for Response and Recovery

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Applied Technology Council

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Preface

Following the two damaging California earthquakes in 1989 (Loma Prieta) and 1994 (Northridge), many concrete wall and masonry wall buildings were repaired using federal disaster assistance funding. The repairs were based on inconsistent criteria, giving rise to controversy regarding criteria for the repair of cracked concrete and masonry wall buildings. To help resolve this controversy, the Federal Emergency Management Agency (FEMA) initiated a project on evaluation and repair of earthquake damaged concrete and masonry wall buildings in 1996. The project was conducted through the Partnership for Response and Recovery (PaRR), a joint venture of Dewberry & Davis of Fairfax, Virginia, and Woodward-Clyde Federal Services of Gaithersburg, Maryland. The Applied Technology Council (ATC), under subcontract to PaRR, was responsible for developing technical criteria and procedures (the ATC-43 project).

The ATC-43 project addresses the investigation and evaluation of earthquake damage and discusses policy issues related to the repair and upgrade of earthquake-damaged buildings. The project deals with buildings whose primary lateral-force-resisting systems consist of concrete or masonry bearing walls with flexible or rigid diaphragms, or whose vertical-load-bearing systems consist of concrete or steel frames with concrete or masonry infill panels. The intended audience is design engineers, building owners, building regulatory officials, and government agencies.

The project results are reported in three documents. The FEMA 306 report, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual,* provides guidance on evaluating damage and analyzing future performance. Included in the document are component damage classification guides, and test and inspection guides. FEMA 307, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources*, contains supplemental information including results from a theoretical analysis of the effects of prior damage on single-degree-of-freedom mathematical models, additional background information on the component guides, and an example of the application of the basic procedures. FEMA 308, *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings*, discusses the policy issues pertaining to the repair of earthquake damaged buildings and illustrates how the procedures developed for the project can be used to provide a technically sound basis for policy decisions. It also provides guidance for the repair of damaged components.

The project also involved a workshop to provide an opportunity for the user community to review and comment on the proposed evaluation and repair criteria. The workshop, open to the profession at large, was held in Los Angeles on June 13, 1997 and was attended by 75 participants.

The project was conducted under the direction of ATC Senior Consultant Craig Comartin, who served as Co-Principal Investigator and Project Director. Technical and management direction were provided by a Technical Management Committee consisting of Christopher Rojahn (Chair), Craig Comartin (Co-Chair), Daniel Abrams, Mark Doroudian, James Hill, Jack Moehle, Andrew Merovich (ATC Board Representative), and Tim McCormick. The Technical Management Committee created two Issue Working Groups to pursue directed research to document the state of the knowledge in selected key areas: (1) an Analysis Working Group, consisting of Mark Aschheim (Group Leader) and Mete Sozen (Senior Consultant) and (2) a Materials Working Group, consisting of Joe Maffei (Group Leader and Reinforced Concrete Consultant), Greg Kingsley (Reinforced Masonry Consultant), Bret Lizundia (Unreinforced Masonry Consultant), John Mander (Infilled Frame Consultant), Brian Kehoe and other consultants from Wiss, Janney, Elstner and Associates (Tests, Investigations, and Repairs Consultant). A Project Review Panel provided technical overview and guidance. The Panel members were Gregg Borchelt, Gene Corley, Edwin Huston, Richard Klingner, Vilas Mujumdar, Hassan Sassi, Carl Schulze, Daniel Shapiro, James Wight, and Eugene Zeller. Nancy Sauer and Peter Mork provided technical editing and report production services, respectively. Affiliations are provided in the list of project participants.

The Applied Technology Council and the Partnership for Response and Recovery gratefully acknowledge the cooperation and insight provided by the FEMA Technical Monitor, Robert D. Hanson.

Tim McCormick
PaRR Task Manager

Christopher Rojahn
ATC-43 Principal Investigator
ATC Executive Director

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Prologue

This document is one of three to result from the ATC-43 project funded by the Federal Emergency Management Agency (FEMA). The goal of the project is to develop technically sound procedures to evaluate the effects of earthquake damage on buildings with primary lateral-force-resisting systems consisting of concrete or masonry bearing walls or infilled frames. The procedures are based on the knowledge derived from research and experience in engineering practice regarding the performance of these types of buildings and their components. The procedures require thoughtful examination and review prior to implementation. The ATC-43 project team strongly urges individual users to read all of the documents carefully to form an overall understanding of the damage evaluation procedures and repair techniques.

Before this project, formalized procedures for the investigation and evaluation of earthquake-damaged buildings were limited to those intended for immediate use in the field to identify potentially hazardous conditions. ATC-20, *Procedures for Postearthquake Safety Evaluation of Buildings*, and its addendum, ATC-20-2 (ATC, 1989 and 1995) are the definitive documents for this purpose. Both have proven to be extremely useful in practical applications. ATC-20 recognizes and states that in many cases, detailed structural engineering evaluations are required to investigate the implications of earthquake damage and the need for repairs. This project provides a framework and guidance for those engineering evaluations.

What have we learned?

The project team for ATC-43 began its work with a thorough review of available analysis techniques, field observations, test data, and emerging evaluation and design methodologies. The first objective was to understand the effects of damage on future building performance. The main points are summarized below.

- **Component behavior controls global performance.**

  Recently developed guidelines for structural engineering seismic analysis and design techniques focus on building displacement, rather than forces as the primary parameter for the characterization of seismic performance. This approach models the building as an assembly of its individual components. Force-deformation properties (e.g., elastic stiffness, yield point, ductility) control the behavior of wall panels, beams, columns, and other components. The component behavior, in turn, governs the overall displacement of the building and its seismic performance. Thus, the evaluation of the effects of damage on building performance must concentrate on how component properties change as a result of damage.

- **Indicators of damage (e.g., cracking, spalling) are meaningful only in light of the mode of component behavior.**

  Damage affects the behavior of individual components differently. Some exhibit ductile modes of post-elastic behavior, maintaining strength even with large displacements. Others are brittle and lose strength abruptly after small inelastic displacements. The post-elastic behavior of a structural component is a function of material properties, geometric proportions, details of construction, and the combination of demand actions (axial, flexural, shearing, torsional) imposed upon it. As earthquake shaking imposes these actions on components, the components tend to exhibit predominant modes of behavior as damage occurs. For example, if earthquake shaking and its associated inertial forces and frame distortions cause a reinforced concrete wall panel to rotate at each end, statics defines the relationship between the associated bending moments and shear force. The behavior of the panel depends on its strength in flexure relative to that in shear. Cracks and other signs of damage must be interpreted in the context of the mode of component behavior. A one-eighth-inch crack in a wall panel on the verge of brittle shear failure is a very serious condition. The same size crack in a flexurally-controlled panel may be insignificant with regard to future seismic performance. This is, perhaps, the most important finding of the ATC-43 project: the significance of cracks and other signs of damage, with respect to the future performance of a building, depends on the mode of behavior of the components in which the damage is observed.

- **Damage may reveal component behavior that differs from that predicted by evaluation and design methodologies.**

  When designing a building or evaluating an undamaged building, engineers rely on theory and their own experience to visualize how earthquakes will affect the structure. The same is true when they evaluate the effects of actual damage after an earthquake, with one important difference. If engineers carefully observe the nature and extent of the signs of the damage, they can greatly enhance their insight into the way the building actually responded to earthquake shaking. Sometimes the actual behavior differs from that predicted using design equations or procedures. This is not really surprising, since design procedures must account conservatively for a wide range of uncertainty in material properties, behavior parameters, and ground shaking characteristics. Ironically, actual damage during an earthquake has the potential for improving the engineer's knowledge of the behavior of the building. When considering the effects of damage on future performance, this knowledge is important.

- **Damage may not significantly affect displacement demand in future larger earthquakes.**

  One of the findings of the ATC-43 project is that prior earthquake damage does not affect maximum displacement response in future, larger earthquakes in many instances. At first, this may seem illogical. Observing a building with cracks in its walls after an earthquake and visualizing its future performance in an even larger event, it is natural to assume that it is worse off than if the damage had not occurred. It seems likely that the maximum displacement in the future, larger earthquake would be greater than if it had not been damaged. Extensive nonlinear time-history analyses performed for the project indicated otherwise for many structures. This was particularly true in cases in which significant strength degradation did not occur during the prior, smaller earthquake. Careful examination of the results revealed that maximum displacements in time histories of relatively large earthquakes tended to occur after the loss of stiffness and strength would have taken place even in an undamaged structure. In other words, the damage that occurs in a prior, smaller event would have occurred early in the subsequent, larger event anyway.

What does it mean?

The ATC-43 project team has formulated performance-based procedures for evaluating the effects of damage. These can be used to quantify losses and to develop repair strategies. The application of these procedures has broad implications.

- **Performance-based damage evaluation uses the actual behavior of a building, as evidenced by the observed damage, to identify specific deficiencies.**

  The procedures focus on the connection between damage and component behavior and the implications for estimating actual behavior in future earthquakes. This approach has several important benefits. First, it provides a meaningful engineering basis for measuring the effects of damage. It also identifies performance characteristics of the building in its pre-event and damaged states. The observed damage itself is used to calibrate the analysis and to improve the building model. For buildings found to have unacceptable damage, the procedures identify specific deficiencies at a component level, thereby facilitating the development of restoration or upgrade repairs.

- **Performance-based damage evaluation provides an opportunity for better allocation of resources.**

  The procedures themselves are technical engineering tools. They do not establish policy or prescribe rules for the investigation and repair of damage. They may enable improvements in both private and public policy, however. In past earthquakes, decisions on what to do about damaged buildings have been hampered by a lack of technical procedures to evaluate the effects of damage and repairs. It has also been difficult to investigate the risks associated with various repair alternatives. The framework provided by performance-based damage evaluation procedures can help to remove some of these roadblocks. In the long run, the procedures may tend to reduce the prevailing focus on the loss caused by damage from its pre-event conditions and to increase the focus on what the damage reveals about future building performance. It makes little sense to implement unnecessary repairs to buildings that would perform relatively well even in a damaged condition. Nor is it wise to neglect buildings in which the component behavior reveals serious hazards regardless of the extent of damage.

- **Engineering judgment and experience are essential to the successful application of the procedures.**

  ATC-20 and its addendum, ATC-20-2, were developed to be used by individuals who might be somewhat less knowledgeable about earthquake building performance than practicing structural engineers. In contrast, the detailed investigation of damage using the performance-based procedures of this document and the companion FEMA 307 report (ATC, 1998a) and FEMA 308 report (ATC, 1998b) must be implemented by an experienced engineer. Although the documents include information in concise formats to facilitate field operations, they must not be interpreted as a "match the pictures" exercise for unqualified observers. Use of these guideline materials requires a thorough understanding of the underlying theory and empirical justifications contained in the documents. Similarly, the use of the simplified direct method to estimate losses has limitations. The decision to use this method and the interpretation of the results must be made by an experienced engineer.

- **The new procedures are different from past damage evaluation techniques and will continue to evolve in the future.**

  The technical basis of the evaluation procedures is essentially that of the emerging performance-based seismic and structural design procedures. These will take some time to be assimilated in the engineering community. The same is true for building officials. Seminars, workshops, and training sessions are required not only to introduce and explain the procedures but also to gather feedback and to improve the overall process. Additionally, future materials-testing and analytical research will enhance the basic framework developed for this project. Current project documents are initial editions to be revised and improved over the years.

In addition to the project team, a Project Review Panel has reviewed the damage evaluation and repair procedures and each of the three project documents. This group of experienced practitioners, researchers, regulators, and materials industry representatives reached a unanimous consensus that the products are technically sound and that they represent the state of knowledge on the evaluation and repair of earthquake-damaged concrete and masonry wall buildings. At the same time, all who contributed to this project acknowledge that the recommendations depart from traditional practices. Owners, design professionals, building officials, researchers, and all others with an interest in the performance of buildings during earthquakes are encouraged to review these documents and to contribute to their continued improvement and enhancement. Use of the documents should provide realistic assessments of the effects of damage and valuable insight into the behavior of structures during earthquakes. In the long run, they hopefully will contribute to sensible private and public policy regarding earthquake-damaged buildings.

1. Introduction and Overview

1.1 Purpose

The purpose of this document is to provide practical criteria and guidance for evaluating earthquake *damage* to buildings with primary lateral-force-resisting systems consisting of concrete or masonry walls or *infilled frames*. The procedures in this manual are intended to characterize the observed damage caused by the earthquake in terms of the loss in building performance capability. This information may be used to facilitate the settlement of insurance claims, the development of strategies for *repair*, or other purposes. The intended users of this document are primarily practicing engineers with experience in concrete and masonry design in seismic regions. Information in this document also may be useful to building owners, building officials insurance adjusters, and government agencies; however these users should consult with a qualified engineer for interpretation or specific application of the document.

1.2 Scope

Concrete and masonry wall buildings include those with vertical-load *bearing wall* panels, with and without openings. This document also applies to buildings with vertical-load-bearing frames of concrete or steel that incorporate masonry or concrete infill panels to resist horizontal forces. For both types of buildings, the procedures and criteria in this document address:

a. The investigation and documentation of damage caused by earthquakes

b. The classification of the damage for building *components* according to mode of structural behavior and *severity of damage*

c. The evaluation of the effects of the damage on the performance of the building during future earthquakes

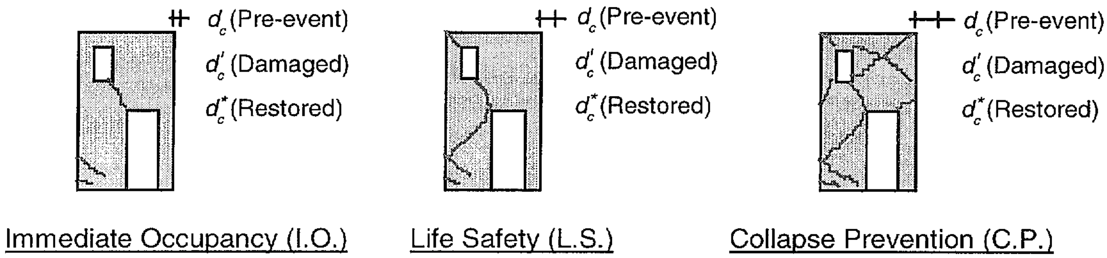
d. The development of hypothetical measures that would restore the performance of the building to that of its condition immediately before the damaging earthquake

Evaluating of the effects of earthquake damage on future seismic performance entails the *relative performance analysis* of the building in its damaged and pre-event states for one or more *seismic performance objectives*. If the expected performance of the damaged building is significantly worse than that anticipated for the building in its pre-event condition, conceptual *performance restoration measures* are developed on a component level to generate global performance nearly equivalent to the pre-event condition. Performance restoration measures rely on the technical analysis of potential component actions. The document also includes a simplified *direct method* for generating an approximate scope for performance restoration measures for some cases. Although performance restoration measures specified by either method are essentially hypothetical physical repairs, they are not recommended for actual implementation solely on the basis of these damage evaluation procedures. The selection of appropriate repairs for an earthquake-damaged building typically requires consideration of a wider range of technical and policy issues. This process is summarized in a companion document, FEMA 308: *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* (ATC, 1998b).

The procedures for damage evaluation in this document are technical; however, their use requires policy considerations including the selection of performance objectives as benchmarks for measuring changes in seismic performance. This document does not specify or limit the use of the damage evaluations, nor does it impose damage repair scope or procedures. Users should not infer otherwise.

Earthquakes can cause damage to the structural and nonstructural components of buildings. This document addresses structural damage. The direct evaluation of nonstructural damage is not included. The effects of structural damage on potential future nonstructural damage can be addressed indirectly by the selection of appropriate seismic performance objectives for the evaluation procedure.

The term *damage*, when used in this document, refers to damage to the building caused by the earthquake. It is important to note that prior effects of environmental deterioration, service conditions, and previous earthquakes are considered to be *pre-existing conditions* and not part of the damage to be evaluated. This distinction is covered further in the presentation of the evaluation procedures.



Notes:
1. Displacement capacity varies depending on performance level and the condition of the building at the time of the earthquake.
2. See Chapter 4 for discussion of performance levels.
3. Pre-event ( ), Damaged ('), and Restored (*) designate the condition of the building at the time of the earthquake.

Figure 1-1 ***Global Displacement Capacities for Various Performance Levels. Capacities will vary, depending on damage level and restoration measure.***

1.3 Basis

The evaluation procedure assumes that when an earthquake causes damage to a building, a competent engineer can assess the effects, at least partially, through visual inspection augmented by investigative tests, structural analysis, and knowledge of the building construction. By determining how the structural damage has changed structural properties, it is feasible to develop potential actions (performance restoration measures) that, if implemented, would restore the damaged building to a condition such that its future earthquake performance would be essentially equivalent to that of the building in its pre-event condition. The costs associated with these conceptual performance restoration measures quantify the loss associated with the earthquake damage.

The damage evaluation procedure measures the effects of damage by comparing the relative capability of pre-event, damaged, and restored models of a building to meet seismic performance objectives for future earthquakes. The analysis technique is to compare a *global displacement capacity* limit, d_c, to a global displacement demand, d_d, for the building model (see Figures 1-1 and 1-2). Both of these global displacement parameters are controlled by the force-deformation properties of all the individual structural components of the building model. The procedure includes techniques for modifying these component force-deformation properties to account for the effects of both the observed damage and potential restoration measures.

The damage evaluation criteria build, to the extent possible, on existing performance-based procedures in the FEMA 273 and FEMA 274 reports, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997a) and companion *Commentary* (ATC, 1997b), and the ATC-40 Report, *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC, 1996). This document adapts the existing state of knowledge rather than developing completely new techniques. This approach contributes to consistency of language, nomenclature, and technical concepts among emerging procedures intended for use by structural engineering practitioners. The intent is to improve the application of the existing knowledge and techniques by using observations of earthquake damage to calibrate analytical models of component behavior.

Two principal research efforts augment the basic procedures:

- An Analysis Working Group has investigated the theoretical effects of prior damage on the displacement response of single-degree-of-freedom models subjected to earthquakes in an effort to verify and/or modify current methods of predicting displacement demand. The implications of the results from this investigation for damage evaluation are reflected in Section 4.4.4 of this volume. A summary report on the results is included in FEMA 307: *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources* (ATC, 1998a).

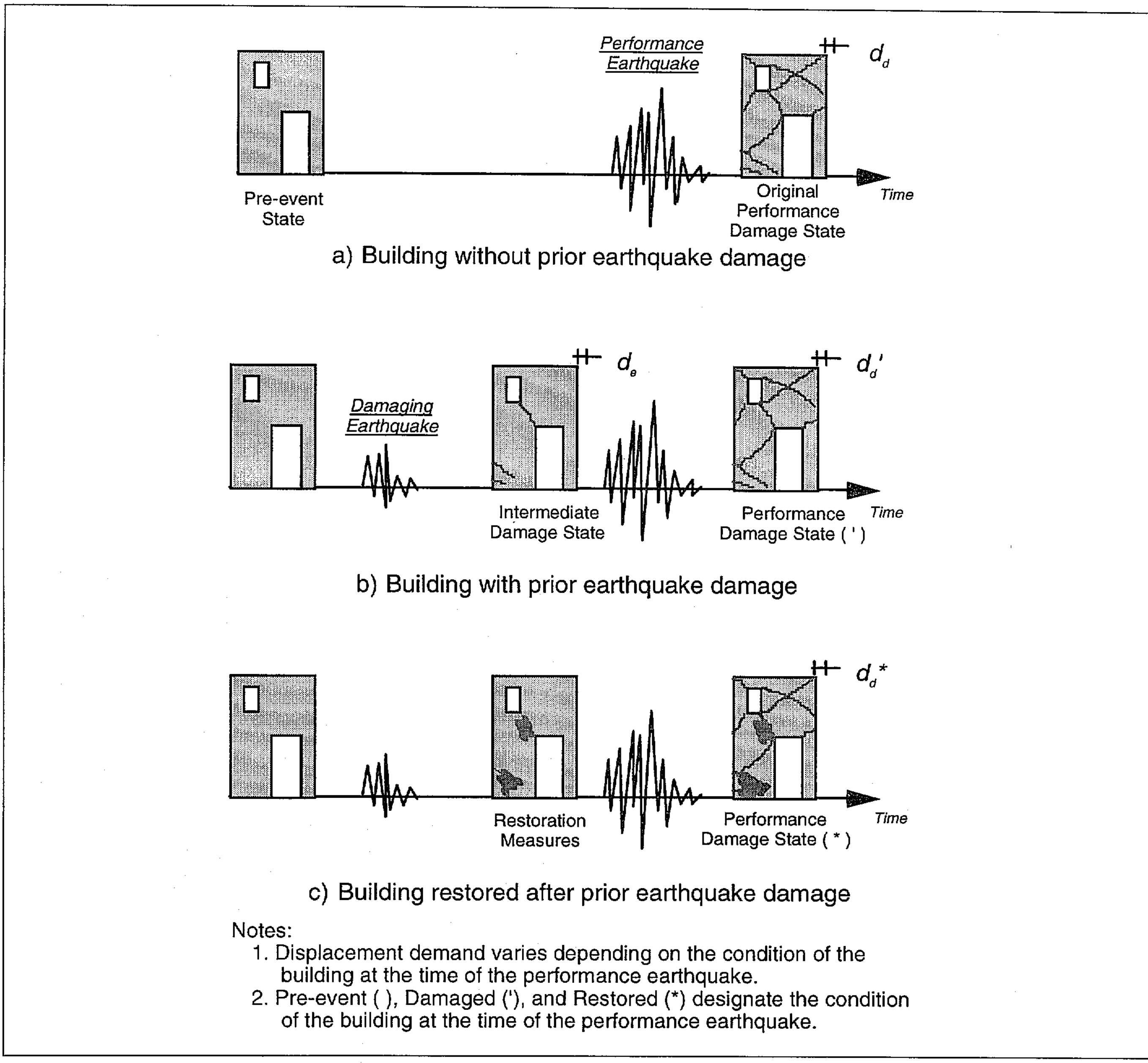


Figure 1-2 ***Global Displacement Demands for Restored and Unrestored Damaged Buildings.***

- A Materials Working Group has assembled tests and investigative techniques to document the effects of earthquake damage. This effort produced the Test and Inspection Guides included in Chapter 3 of this volume. This group also used existing research results to develop recommended modifications to component force-deformation relationships for nonlinear structural analysis to include the effects of damage. The results are the Component Damage Classification Guides included in Chapters 5 through 8. Additional background information including that forming the basis of the Component Guides is in FEMA 307 (ATC, 1998a). Finally this group assembled information on repair techniques commonly applied to earthquake damage in concrete and masonry wall buildings. These are documented in a companion document, FEMA 308: *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* (ATC, 1998b).

In the past, there has been a tendency to gauge the effect of earthquake damage by estimating the loss of lateral-force-resisting capacity of the structure (Hanson, 1996). It has been suggested by some that this loss can be related to the observed width and extent of concrete and masonry cracks in the damaged structure. There has been widespread disagreement on the significance of cracking on capacity and skepticism on the suitability of force capacity as a parameter for measuring damage. The procedure in this document is based on global displacement and component deformation capacities rather than force capacities. This approach facilitates a more meaningful engineering assessment of the effects of damage on future performance.

1.4 Overview of the Damage Investigation and Evaluation Procedures

This section briefly summarizes the damage investigation and evaluation procedures, referring as necessary to specific chapters. One objective is to provide the practicing engineer with a road map for the use of the document in real-life applications. Another equally important objective is to provide a basic exposure to the process for owners, building officials, disaster assistance personnel, and others with an interest in the results who may not be familiar with the technical details.

1.4.1 Introduction and Overview

Chapter 1 summarizes the purpose, basis, and scope of the document. The technical basis of the damage investigation and evaluation procedures are reviewed. A step-by-step outline presents these basic procedures. Brief synopses are included for subsequent chapters.

1.4.2 Characteristics of Concrete and Masonry Wall Buildings

Chapter 2 presents a summary of the characteristic features of concrete and masonry wall buildings. The chapter introduces the concept of structural systems, *elements* and components that is used throughout the evaluation process. The discussion includes the distinction between bearing walls and infilled frames. The effect of the dimensional and material characteristics of the wall components and the importance of this concept for the investigation of the damage caused by an earthquake are discussed. This chapter also illustrates the formulation of an *inelastic lateral mechanism* for a building based on the properties of its individual components. Additionally, the chapter discusses how observed damage can be used to enhance and augment the model used for the investigation process.

1.4.3 Investigation of Earthquake Damage

The initial effort in the evaluation of damage to a specific building concentrates on investigating and documenting the damage that has occurred to a building during the earthquake (see Figure 1-3). Investigation procedures are given in Chapter 3. The objective is to assemble the basic information in a format that facilitates its use in evaluating the effects of the damage on future seismic performance. The primary steps in the investigation are summarized below.

1.4.3.1 Assemble Information

The first step in the investigation is a compilation of basic information on the damaging earthquake and the building.

A. Damaging Earthquake

Performance-based evaluations rely on a comparison between the capacity of a building to sustain lateral movement and the demand for lateral movement imposed by the *performance ground motion*. Information about the performance characteristics of a building can be derived from estimating the displacement demand that the damaging earthquake placed on it. For example, the decision regarding repair or upgrading of a building with moderate damage is affected by the magnitude of shaking that caused the damage. Section 3.1 provides a summary of suggestions for characterizing the *damaging ground motion* at the site for subsequent analysis.

B. Building Data

A discussion of the common configuration characteristics and components of concrete and masonry wall buildings is given in Chapter 2. The focus of the damage investigation is on the structural components that make up the vertical- and lateral-force-resisting system for the specific building under investigation. The construction drawings for the building, soils reports, prior building inspections, and other relevant reports and documents are the primary sources of the pertinent information (see Section 3.2). Basic information about the building includes its age, size, and use. If it was inspected after the damaging earthquake for posting purposes, these data can be

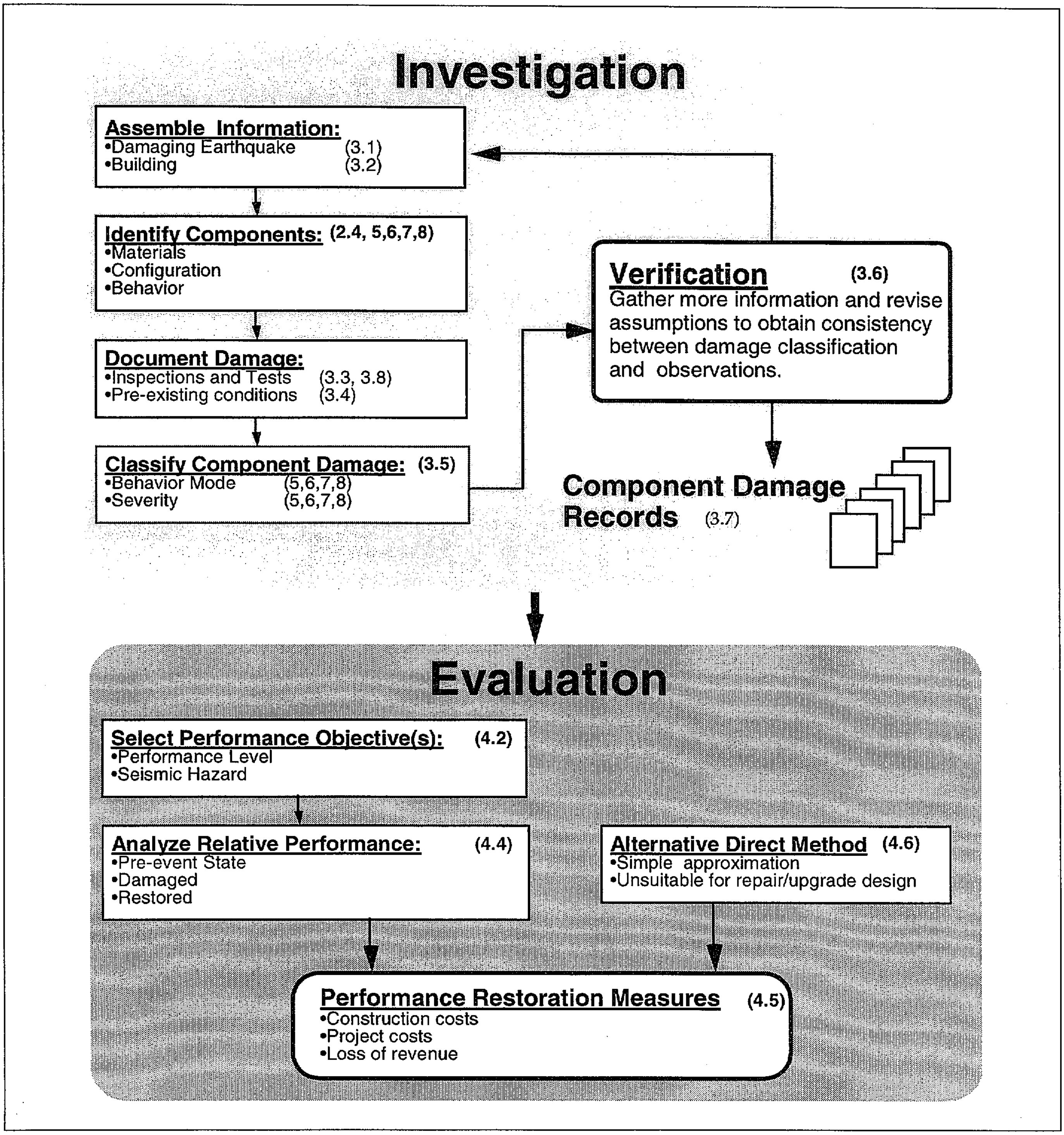


Figure 1-3 Flowchart for the Investigation and Evaluation of Earthquake Damage to Concrete and Masonry Wall Buildings. (Section numbers are indicated.)

useful. If records of the operation and maintenance are available, they can be useful in distinguishing between pre-existing conditions and damage caused by the earthquake.

C. Performance Objectives

The evaluation procedures are based on the performance objective for the building (see Section 4.2). Although it is possible to investigate and document damage without choosing a performance objective, it is worthwhile to consider this issue early in the evaluation process.

1.4.3.2 Identify Components

The engineer identifies basic structural components by anticipating the governing mechanism of inelastic behavior for each element in the structural system. This process normally requires some basic calculations to compare the relative strength and stiffness of the individual components of the structure . For each type of wall material (reinforced concrete, reinforced masonry, and unreinforced masonry) and for infilled frames, there are a number of basic component types. These are compiled in Chapters 5, 6, 7, and 8.

1.4.3.3 Document Damage

After assembling and reviewing available data, the engineer documents the actual damage based on field inspections and tests. Section 3.8 provides a compilation of outline specifications for different types of tests and investigative procedures. It includes guidance on the selection of appropriate procedures, equipment and personnel requirements, report format, and interpretation of results.

1.4.3.4 Classify Component Damage

For each component of the structural system, the engineer classifies the damage according to *behavior mode* and severity. The various behavior modes for each material and framing type are tabulated in Component Damage Classification Guides in Chapters 5, 6, 7, and 8. The engineer also categorizes the severity of damage for each type of damage encountered within any component.

1.4.3.5 Verification

The investigation of damage is a cyclic process. Information from the field can help the engineer determine component type based on actual behavior. Calculations and analyses can also help with the interpretation of field data. In some cases, the engineer may decide to conduct further tests to resolve conflicting data. Properly implemented, the process concludes with a reasonable representation of the actual damage and a basic understanding of the response of the structure to the earthquake shaking.

1.4.4 Evaluation of Earthquake Damage

Chapter 4 provides guidance on how to evaluate the significance of the observed damage. A seismic performance objective (see Section 4.2) consists of a specific *performance level* (e.g., *collapse prevention, life safety*, or *immediate occupancy*) for a specific seismic hazard (probability of shaking of a given intensity, or a deterministic event). The damage evaluation procedure uses a specified performance objective as a benchmark to gauge the effects of damage. The selection of applicable performance objectives for a building is a policy decision that depends on its age, size, use, and other considerations. For some cases, consideration of multiple performance objectives is appropriate.

Once the effects of the damaging ground motion on all of the components are tabulated, the engineer quantifies these effects for the entire building by determining the scope of actions that, if implemented, would restore the future seismic performance of the building to that of its pre-event state. These are performance restoration measures and they are the subject of Chapter 4. These measures are formulated by detailed analysis of the building in its pre-event, damaged, and restored conditions (i.e., relative performance analysis). In some cases a simplified approach (i.e., direct method) may be applicable to generate an estimate of loss. The selection of the appropriate method for a building depends on a number of considerations, including the severity of the earthquake, the extent and type of damage, and the likely course of action for repair or upgrade of the building.

The performance restoration measures determined by either the relative performance analysis or the direct method represent the conceptual physical changes to the damaged structure that would be required to restore the performance to the level that existed before the damaging earthquake. The loss in future seismic performance caused by the damaging earthquake is measured by the hypothetical costs to implement these measures. The total loss includes indirect costs, such as design and management fees and loss of use of the facility, in addition to direct construction costs that would be associated with the performance restoration measures if they were to be implemented.

Section 4.4 addresses the technical aspects of seismic performance analysis of concrete and masonry wall buildings. This quantitative procedure uses nonlinear analysis techniques to estimate the performance of the building in future earthquakes in its pre-event, damaged and restored states. The force-deformation characteristics of components are modified to account for damage according to recommendations in the Component Damage Classification Guides in Chapters 5 through 8. In order to determine the scope of the performance restoration measures, the engineer analyzes selective component restoration measures as well as the possible addition of supplemental components with the objective of restoring the seismic performance to that of the pre-event building.

1.4.5 Component Information

1.4.5.1 Component Damage Classification Guides

Chapters 5, 6, 7, and 8 provide a compilation of Component Guides for use in the damage evaluation process. These assist the engineer in identifying the structural components, determining behavior modes, and gauging damage severity. The guides also provide information on how damage affects the force-deformation characteristics of the components. This information is for use in the performance analysis. Recommendations for measures to restore structural properties are also tabulated. The component guides are classified according to structural system. The four classifications are:

- Concrete (Chapter 5)
- Reinforced masonry (Chapter 6)
- Unreinforced masonry (Chapter 7)
- Infilled frames (Chapter 8)

1.4.6 Terms and Symbols

A conscientious effort has been made to utilize concepts and language that are familiar to practicing engineers. This document, however, introduces terms whose definitions are not necessarily in common use. Such items, italicized at their first occurrence, are defined in the Glossary.

To the extent possible this document uses common symbols and notation that are familiar to practicing engineers. New symbols are required in some instances. These are listed at the end of this document. Symbols related primarily to specific materials are listed at the end of Chapter 5 for concrete, Chapter 6 for reinforced masonry, Chapter 7 for unreinforced masonry, and Chapter 8 for infilled frames.

1.4.6.1 Test and Inspection Guides

Section 3.8 presents information on common tests and inspection methods for investigation of earthquake damage to concrete, masonry wall, and infill frame buildings. It includes summaries of the required equipment and personnel, and the objectives and limitations of the procedures are reviewed. Reference and resource materials are listed.

1.4.7 Related Documents

FEMA 307: *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources* (ATC, 1998a)

FEMA 307 provides additional detailed information on the basis and use of the damage-evaluation procedures of FEMA 306. Background information on the development of the Component Guides is included for each material type and for infilled frames. It is essential that the engineer understand this information both for the general application of the procedures and for special cases when the typical component data must be modified to suit actual conditions. A summary of the analytical studies on the effects of damage on the global response of buildings is provided. This information is the basis for the recommendations on determining seismic displacement demand contained in FEMA 306. Finally, damage evaluation of a specific building is presented as a practical illustration of the application of the procedures.

FEMA 308: *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* (ATC, 1998b)

This document supplements the evaluation procedures with a summary of policy considerations on the repair of earthquake-damaged concrete and masonry wall buildings. A model framework for repair policy is developed from past experience with damaging earthquakes. The use of the information from the evaluation process within this framework is illustrated for both the private and public sectors. The alternatives for repairing and upgrading earthquake-damaged buildings are reviewed along with potentially applicable standards and methodologies. Outline specifications for typical repair techniques are provided. Information on the objectives and limitations of the procedures is summarized. Reference standards and quality assurance measures are tabulated. These Repair Guides are also intended for use in the damage evaluation process to assist in the development of performance restoration measures.

ATC-20: *Procedures for the Post Earthquake Safety Evaluation of Buildings* (ATC, 1989)

ATC-20 is the standard for the safety investigation of buildings immediately following an earthquake. The intent of the document is to determine by visual observation of damage whether buildings are safe to occupy shortly after the earthquake. There are three levels of possible evaluation implied in ATC 20. The first level, Rapid Evaluation, is an inspection of the damage, which is intended to be implemented by building officials, engineers, architects, inspectors, or other individuals with a general familiarity with building construction. Questionable structures may be then subject to Detailed Evaluation by a structural engineer. If a structure cannot be appraised effectively by visual techniques alone, an Engineering Evaluation is required. At the time that ATC-20 was published, guidelines for Engineering Evaluations were not available. The procedures in FEMA 306 may be effectively utilized by qualified structural engineers to fill this gap. Consequently, FEMA 306 supplements the provisions of ATC-20.

1.5 Limitations

The procedures and criteria for the evaluation of damage in this document have been developed based on the current state of the knowledge on nonlinear inelastic behavior of structures and structural components. The state of knowledge varies by material, component type, and mode of behavior as discussed in Chapters 5, 6, 7, and 8 and FEMA 307. This knowledge will expand over time. The evaluation procedures and the information on component behavior must be adapted appropriately to reflect new information.

The interpretation of damage and the performance of buildings subject to earthquakes benefits from considerable experience and expert judgment. These procedures and criteria provide a framework for an engineer to apply experience and to formulate judgments on the effects of earthquake damage on future performance. The limitations of the procedures notwithstanding, the relative validity of results for a given situation are predominantly dependent on the capabilities of the engineer or engineers. The procedures should not be applied by non-engineering personnel (e.g., inspectors, insurance adjusters, claims managers).

In the past, other methodologies have been used to evaluate buildings damaged in earthquakes and to design repairs. If the procedures and criteria of this document are applied retroactively to such buildings, the results may be different. Any difference is not necessarily a reflection on the competency of the individual or firm responsible for the original work. Prior repairs should be judged on the basis of the procedures and criteria that were available at the time of the work.

2. Characteristics of Concrete And Masonry Wall Buildings

This chapter describes the basic design and construction features of concrete and masonry wall buildings. Descriptions of typically encountered structural components for various material types serve as a guide for the user when investigating actual buildings.

The evaluation of damage to a building requires an understanding on the part of the engineer of the way in which it supports gravity loads, resists earthquake forces, and accommodates related displacements. It is helpful to imagine the global building structure as an assembly of elements (see Figure 2-1). An element is a vertical or a horizontal portion of a building that acts to resist lateral and/or vertical loads. Common vertical elements in concrete and masonry wall buildings include structural walls and combined frame-wall (infilled) elements. Common floor or roof horizontal elements are reinforced concrete or wood diaphragms. For evaluation and analysis purposes, each element acts in its own plane to transmit seismic actions through the building in a three-dimensional global assembly of two-dimensional elements. Although out-of-plane seismic actions can act on elements at the same time, these actions are conventionally considered separately.

Elements are themselves assemblies of individual components such as beams, slabs, columns, joints, and others. The global performance of the structural system is an aggregation of the performance of its components. For seismic performance analysis, structural properties (force-deformation relationships) and acceptability criteria (deformation limits) are specified for components. The global behavior of the building depends on these component properties. Evaluation procedures tabulate damage type and severity for components. The identification of components (see Section 2.4) of the lateral-force-resisting elements normally requires some basic engineering analysis and consideration of the type of damage that may have occurred.

2.1 Typical Vertical Elements

Concrete and masonry wall buildings rely primarily on the walls as vertical elements for lateral seismic resistance. The construction of these elements varies by material and the basic system for vertical load transfer. Behavior and damage characteristics of the walls during earthquakes depend on the physical dimensions and configuration of the wall elements including openings and penetrations.

2.1.1 Bearing Walls and Infilled Frames

In concrete and masonry wall buildings, there are two basic systems through which vertical loads are transmitted from the roofs and floors to the foundations:

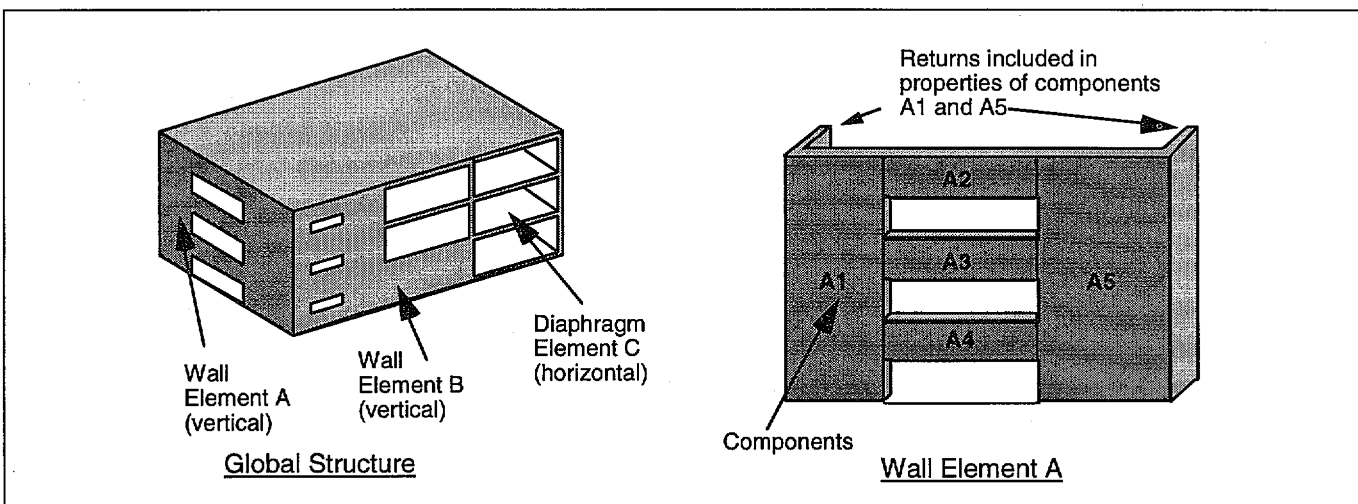


Figure 2-1 ***Global Structure, Lateral-Force-Resisting Elements, and Components.***

bearing walls and infilled frames (see Figure 2-2). Bearing walls may support a portion of adjacent vertical load, as well as their own weight. In some areas of a bearing wall building, supplemental frames, columns, and/or flat slabs might support a portion of the vertical load. The walls themselves can be made of reinforced or unreinforced concrete or masonry.

Infilled frames differ from bearing walls in that they always include a vertical load carrying frame of concrete or steel beams and columns. Wall panels are placed within the frame. The infill can be reinforced or unreinforced concrete or masonry. To be effective at resisting in-plane lateral loads, the infill must be in contact with the surrounding frame. In basic configuration (e.g., distribution of elements within a building, extent of openings in walls), bearing wall and infilled frame buildings often appear similar. Reinforced concrete or masonry bearing walls can have boundary elements that are wider than the wall itself that resemble beams or columns of a frame. Their details of construction and behavior of bearing walls and infilled frames under lateral loads, however, can be quite different. The basic components of bearing wall and infilled frame buildings also differ from one another, as detailed further in Chapters 5, 6, 7, and 8.

2.1.2 Wall Elevations

The elevations of Figure 2-3 illustrate three general categories of concrete and masonry wall element configurations. Each of these configurations may be built of bearing wall or infilled frame construction. Cantilevered walls are those that act predominantly as vertical beams restrained at their foundation level. This is not to imply fixity at the base. In fact, many wall elements are sensitive to foundation movements caused by uplift, soil displacements, or deformations of foundation components, as discussed in Section 2.1.3.

Coupled walls or wall elements are those with a generally regular pattern of openings that form a configuration of vertical (*piers*) and horizontal (*spandrels* or coupling beams) components similar to a frame element. The inelastic action of a coupled wall element consequently depends on the relative strength and stiffness of the pier and spandrel components.

Perforated walls or wall elements may also exhibit an irregular pattern of openings in contrast to coupled walls. If the total area of opening relative to wall area is small, their behavior tends toward that of cantilevered walls. This behavior is illustrated by the strongly coupled perforated wall in Figure 2-4. When there is a relatively large proportion of wall openings, behavior tends toward that of coupled walls with irregular (semi-vertical and semi-horizontal) components. This behavior is illustrated by the weakly coupled perforated wall in Figure 2-4. The modeling of perforated walls requires judgment and experience. Strut and tie models can be used to analyze walls with an irregular pattern of penetrations (Pauley and Priestley, 1992). Observations of damage after an earthquake can provide valuable evidence to assist the engineer in formulating a model to reflect actual behavior.

When walls intersect to form L-shaped, T-shaped, C-shaped, or similar sections, typically the entire section is considered as an integral unit and a single component. The contribution of flanges and wall returns should be considered in evaluating the strength of the component, based on the guidelines given in Chapters 5 through 8.

2.1.3 Foundation Effects

Foundation flexibility and deformation affect the earthquake response of many concrete and masonry wall buildings. Foundation effects tend to reduce the force demand on the primary lateral-force-resisting elements such as *shear walls*. At the same time, however, the rotational flexibility of the base of the shear walls often results in larger lateral displacements of the entire structure. The larger drifts can lead to damage in the beams, columns, or slabs. There is evidence of this type of damage from past earthquakes. Fixed-base analysis techniques do not adequately model these effects. FEMA 273/274 (ATC, 1997a,b) and ATC-40 (ATC, 1996) contain recommendations for modeling foundation elements and components similarly to other structural components.

2.2 Horizontal Elements

Horizontal elements (diaphragms) typically interconnect vertical elements at floor and roof levels in concrete and masonry wall buildings. Reinforced concrete slabs and the associated framing comprise relatively rigid diaphragms. These rigid diaphragms are characteristic of many concrete and masonry wall buildings. For analysis purposes, the flexibility of these diaphragms is often neglected, and the vertical elements are assumed to be rigidly linked at floor and roof levels. While this assumption is tolerable for most buildings, concrete diaphragms are not always rigid and can be

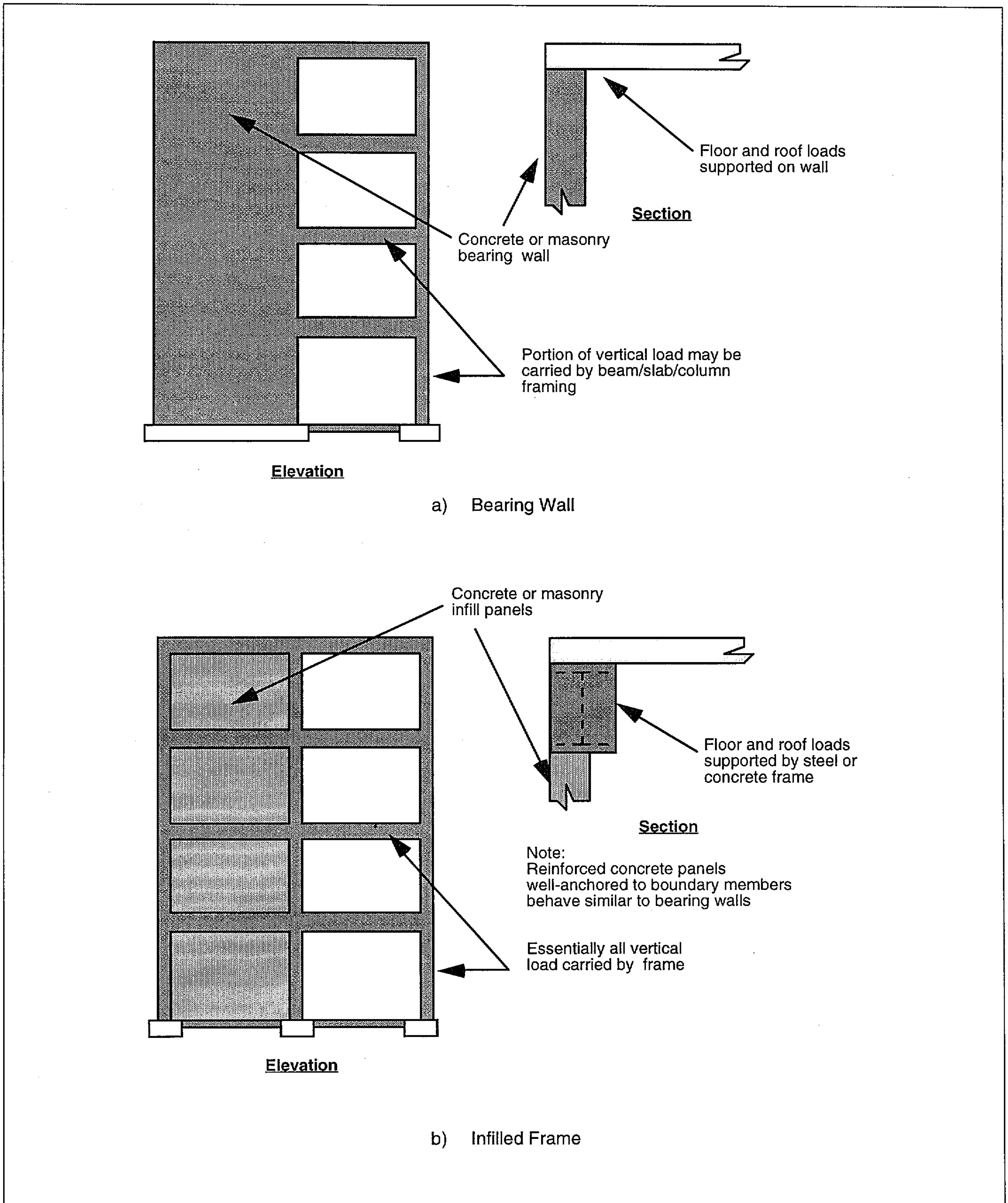


Figure 2-2 Characteristics of Bearing Walls and Infilled Frames

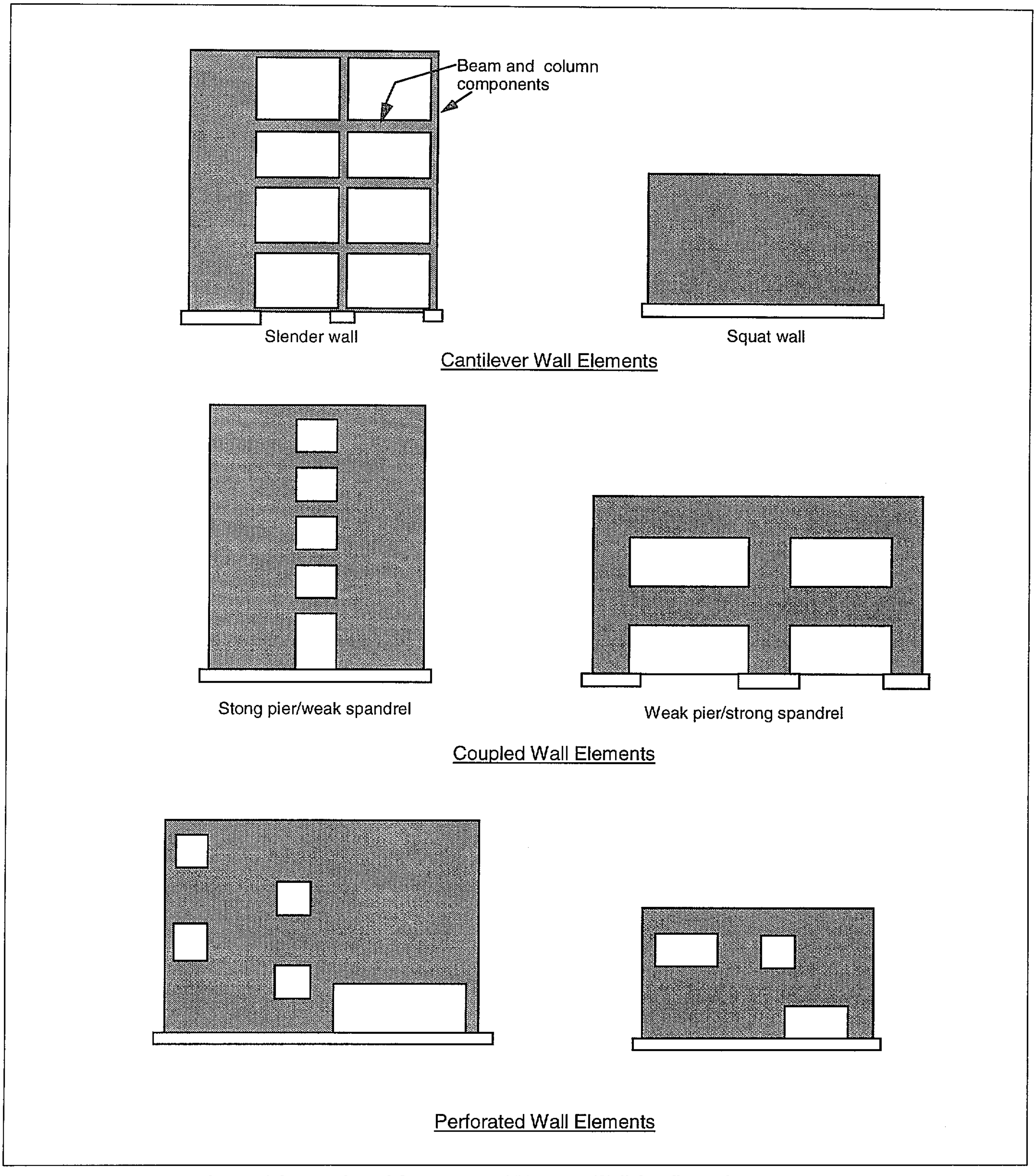


Figure 2-3 Three General Categories of Concrete and Masonry Wall Configurations

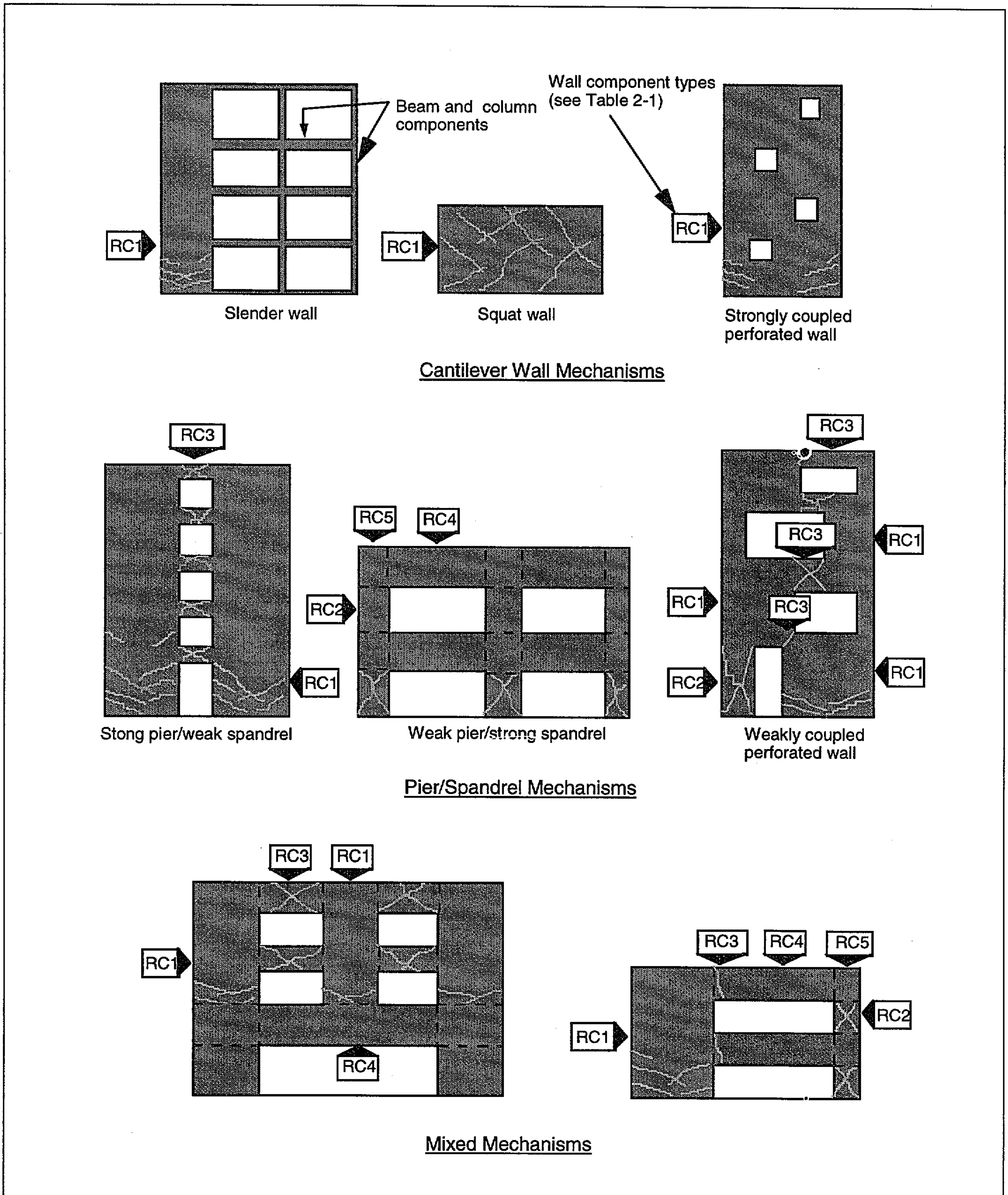


Figure 2-4 ***Example Wall Mechanisms and Components***

damaged in earthquakes. Such damage has been observed, and repair may be required in some cases.

Many unreinforced masonry and precast (tilt-up) reinforced concrete bearing wall buildings have flexible diaphragms of wood sheathing. Walls resist the in-plane lateral loads that are distributed based on the tributary area. Connections between flexible diaphragms and walls are frequently the weak links in the lateral load path of the building, for forces both parallel and perpendicular to the wall. These connections are not addressed specifically in this document, but damage evaluations should consider the potential at these locations. Guidance may be found in FEMA 273/274.

2.3 Three-Dimensional Considerations

The interpretation of earthquake damage in concrete and masonry wall buildings can be complicated by the three-dimensional response of the buildings.

- Global horizontal torsion of the building can affect the distribution of damage to vertical elements. Analysis techniques contained in FEMA 273/274 and ATC-40 that can account for this effect are helpful for damage evaluation. However, the magnitude of the actual torsional response may differ from the estimates (actual plus accidental torsion) conventionally used for design. Careful interpretation of the distribution of damage in the field is required to interpret the torsional behavior.

- Damage to individual elements and components can be due to actions from either, or both, orthogonal directions. For example, a shear wall element acting parallel to one orthogonal direction may include a perpendicular return at either or both ends. Damage to the perpendicular return can be due to forces in either direction and must be carefully interpreted.

- Wall elements and components are subject to both in-plane and out-of-plane earthquake forces. Cracking or other damage due to out-of-plane forces can be misinterpreted as an in-plane effect. If cracks are evident on only one side of a wall element, they may be due to out-of-plane forces.

As a separate issue, parapets and other building appendages can pose serious risks, particularly in unreinforced masonry buildings.

2.4 Identification of Components

The procedures for damage evaluation focus on the components of the building that resist earthquake shaking. The identification of these components is central to the overall evaluation process. The ultimate identification of components for an earthquake-damaged building entails a combination of theoretical analysis and observation of the damage itself.

At the beginning of the evaluation process, the engineer identifies basic components by anticipating the governing inelastic lateral mechanism for each element in the lateral-force-resisting system. This analysis consists of determining the relevant stiffness and ultimate strength (flexure, shear, axial) of each component to anticipate the behavior and geometry of the mechanism that would form as the element is displaced laterally by a monotonically increasing lateral load pattern. Reinforced concrete wall component types are summarized in Table 2-1 and Figure 2-4. The component strength and load patterns are initially assumed using conventional sources including FEMA 273/274, ATC-40, and consensus design standards. FEMA 273/274 and ATC-40 also provide guidance on foundation components.

For each basic material, there are a number of component types. Chapters 5, 6, 7, and 8 provide a compilation of component data by material and framing type. The data in these chapters are supplemented in FEMA 307 by expanded information on component behavior that is based on available test data and theoretical techniques that go beyond conventional design standards. This resource material is useful when the effects of damage are introduced into the evaluation process, as discussed in Section 3.5.

Table 2-1 Component Types for Reinforced Concrete Walls

Component Type		Description
RC1	Cantilever wall or stronger wall pier	This type of component is stronger than beam or spandrel components that may frame into it, so that nonlinear behavior (and damage) is generally concentrated at the base, with a flexural plastic hinge or shear failure. This category includes isolated (cantilever) walls. If the component has a major setback or reduction of reinforcement above the base, this location should be also checked for nonlinear behavior.
RC2	Weaker wall pier	This type of component is weaker than the spandrels to which it connects. Damage is characterized by flexural hinging at the top and bottomof the pier, or by shear failure.
RC3	Weaker spandrel or coupling beam	This type of component is weaker than the wall piers to which it connects. Damage is characterized by hinging at each end, shear failure, or sliding shear failure.
RC4	Stronger spandrel	This type of component should not suffer damage because it is stronger than attached piers. If such a component is damaged, it should be re-classified as RC3.
RC5	Pier-spandrel panel zone	This component is a pier-spandrel connection zone. High shear forces in this zone can cause cracking. Severe damage is uncommon in reinforced concrete and masonry.

3. Investigation of Earthquake Damage

This chapter describes the investigation and documentation of earthquake damage to concrete and masonry wall or infill frame buildings. The objectives of the investigation are listed below.

- To gather information on the characteristics of the damaging ground motion at the building site
- To verify the general physical characteristics of the building, including its geometry and mass
- To identify structural components and elements of the lateral-force-resisting system
- To determine structural properties of the components in sufficient detail for structural analysis purposes
- To observe and record damage to the components
- To distinguish, to the extent possible, between damage caused by the earthquake and damage that may have existed before

The process includes the assembly and review of available existing information relating to the characteristics of the earthquake, assembly and review of information on the structural condition of the building both immediately before and after the earthquake, inspections and tests to characterize the nature and extent of damage, and the documentation and interpretation of the results of the investigation.

3.1 Characteristics of the Damaging Earthquake

During the evaluation of damage to concrete or masonry wall buildings, information on the characteristics of the damaging earthquake can lead to valuable insight on the performance characteristics of the structure. For example, if the ground motion caused by the earthquake can be estimated quantitatively, the analysis techniques summarized in Chapter 4 can provide an estimate of the resulting maximum displacement of the structure. This displacement, in conjunction with the theoretical capacity curve, indicates an expected level of component damage. If the observed component damage is similar to that predicted, the validity of the theoretical model is verified in an approximate manner. If the damage differs, informed adjustments can be made to the model.

A general process for gathering information and evaluating the effects of a damaging earthquake is outlined below:

1. Collect information on the damaging earthquake. If strong motion data is available, it is preferable to use data
   a. from a record taken at or very near to the site, or
   b. from contour maps of ground motions parameters, such as those shown in Figures 3-2, 3-3, and 3-4, created from a spatial interpolation of all nearby strong-motion data.

   If strong-motion data is not available, contours of intensity (e.g., Modified Mercalli Intensity) could be used to estimate spectral accelerations.

   Attenuation relationships can also be used to estimate ground-motion parameters. However, the scatter inherent in such relationships can lead to a large uncertainty in the prediction of ground motion for an individual site.

   In all cases, site soil conditions should be considered in the estimate of ground motion.
2. Formulate an approximate response spectrum for the site (see Figures 3-1 through 3-4). The example in the figures uses the acceleration at a period of 0.3 second to define the acceleration response regime. The 1997 *NEHRP Recommended Provisions for New Buildings* (BSSC, 1997) uses 0.2 second. Either approach may be used depending on the available data.
3. Generate a capacity curve for the structure at the time of the damaging earthquake (see Chapter 4)
4. Use *nonlinear static procedures* to estimate the maximum global displacement, d_e, that the damaging earthquake should have generated for the structure.
5. Estimate the expected component damage for the maximum global displacement of d_e and compare to the observed damage.

3.2 Review of Existing Building Data

The data collection process begins with the acquisition of documents describing the pertinent conditions of the building. Review of construction drawings simplifies

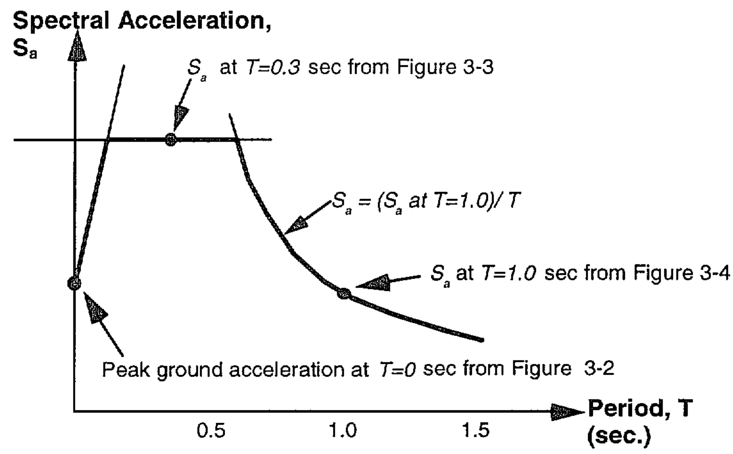


Figure 3-1 ***Parameters Needed and Form of Approximate Site Response Spectrum***

field work and leads to a more complete understanding of the building. Original architectural and structural construction drawings are central to an effective and efficient evaluation of damage. Potential sources of these and other documents include the current and previous building owners, building departments, and the original architects or engineers. Drawings may also be available from architects or engineers who have performed prior evaluations for the building. In addition to construction drawings, it is helpful to assemble the following documents if possible:

- Site seismicity/geotechnical reports
- Structural calculations
- Construction specifications
- Contractors' shop drawings and other construction records
- Foundation reports
- Prior building assessments

Review of the existing building information serves several purposes. If reviewed before field investigations, the information facilitates the analytical identification of structural components, as discussed in Section 2.4. This preliminary analysis also helps to guide the field investigation to components that are likely to be damaged. Existing information can also help to distinguish between damage caused by the earthquake and pre-existing damage. Finally, the scope of the field inspection and testing program depends on the accuracy and availability of existing structural information. For example, if structural drawings reliably detail the size and placement of reinforcing, expensive and intrusive tests to verify conditions in critical locations may be unnecessary.

3.3 Assessing the Consequences of the Damaging Earthquake

Methods for inspecting and testing concrete and masonry wall buildings for earthquake damage fall into two general categories, nondestructive and intrusive. Nondestructive techniques do not require any removal of the integral portions of the components. In some cases, however, it may be necessary to remove finishes in order to conduct the procedure. In contrast, intrusive techniques involve extraction of structural materials for the purpose of testing or for access to allow inspection of portions of a component. Table 3-1 summarizes the types of inspections and tests that apply to concrete and masonry wall buildings.

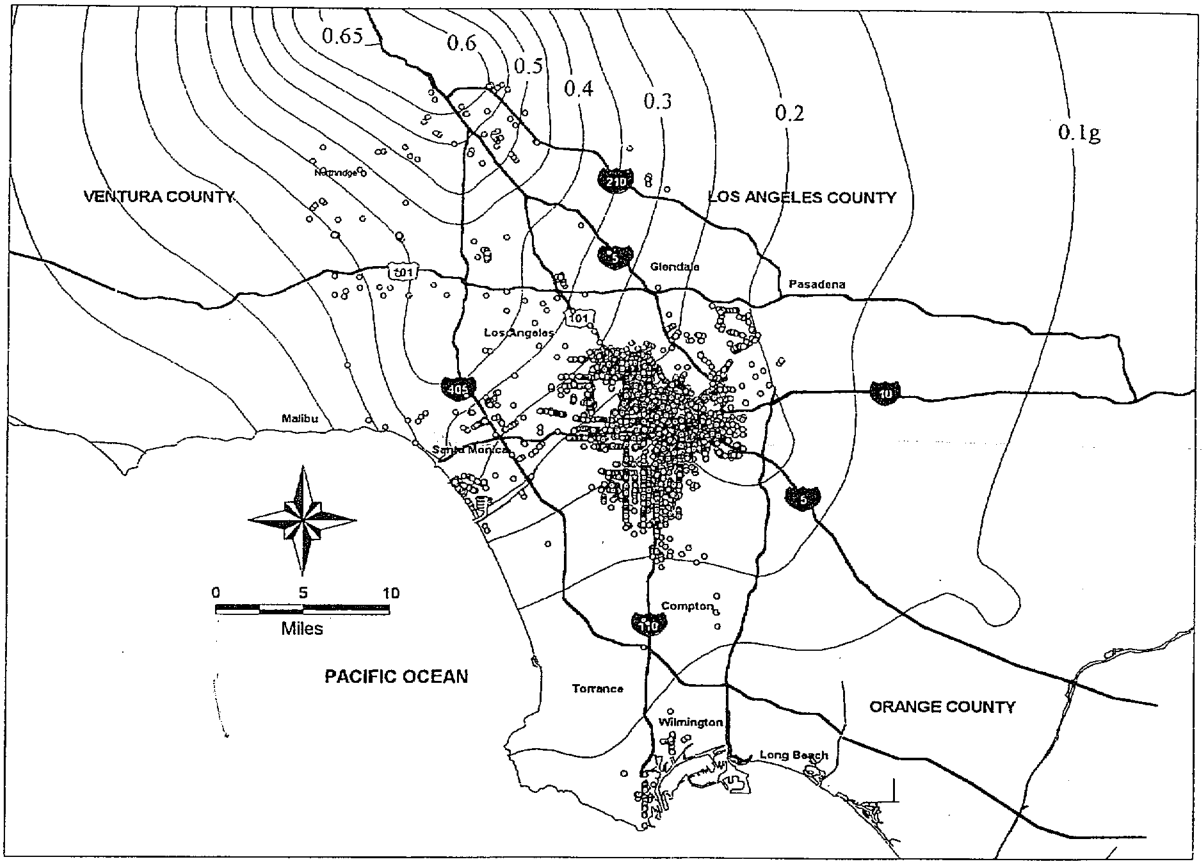


Figure 3-2 ***Peak Ground Acceleration Contours for 1994 Northridge, California, Earthquake (from NIST, 1997, "dots" indicate locations of a particular building type)***

Section 3.8 provides guides for each procedure. Each guide includes a basic background for the practicing engineer on selecting and implementing appropriate procedures based on the actual conditions encountered in the field. Each guide consists of the following information:

Test Name and ID	For reference and identification
Test Type	Nondestructive (NDE) or Intrusive (IT)
Materials	Applicability to reinforced concrete, reinforced masonry, and/or unreinforced masonry
Description	Basic overview of the objectives and scope of the procedure
Equipment	A summary of the tools, instrumentation, or devices required
Execution	General sequence of operations
Reporting Requirements	Format for reporting of results
Personnel Qualifications	Skill level and specialized training that may be required
Limitations	Restrictions on the type of information that can be gained and advice on the interpretation of results
References	Applicable standards, detailed specifications, or sources of additional information

Table 3-1 ***Summary of Inspection and Test Procedures***

Structural Or Material Property	Material			Test ID	Test Type
	Reinf. Conc.	Reinf. Mas.	URM	(Section 3.8)	
Crack Location and Size	✓	✓	✓	NDE 1	Visual observation
Spall Location and Size	✓	✓	✓	NDE 1	Visual observation
	✓	✓	✓	NDE 2	Sounding
Location of Interior Cracks or Delaminations	✓	✓	✓	NDE 6	Impact echo
	✓			NDE 7	Spectral Analysis of Surface Waves
	✓	✓	✓	IT 1	Selective removal
Reinforcing Bar Buckling or Fracturing	✓	✓		NDE 1	Visual observation
	✓	✓		IT 1	Selective removal
Relative Age of Cracks	✓	✓	✓	IT 2	Petrography
Relative Compressive Strength	✓	✓	✓	NDE 3	Rebound hammer
Compressive Strength	✓	✓	✓	IT 3	Material extraction and testing
Reinforcing Bar Location and Size	✓	✓		NDE 4	Rebar detector
	✓	✓		NDE 8	Radiography
	✓	✓		NDE 9	Penetrating radar
	✓	✓		IT 1	Selective removal
Strength of Reinforcing Bar	✓	✓		IT 3	Material extraction and testing
Wall Thickness	✓	✓	✓	NDE 1	Visual observation
	✓	✓	✓	NDE 6	Impact echo
	✓	✓	✓	IT 1	Selective removal
Presence of Grout in Masonry Cells		✓	✓	NDE 2	Sounding
		✓	✓	NDE 6	Impact echo
		✓	✓	NDE 7	Spectral Analysis of Surface Waves
		✓	✓	IT 1	Selective removal
Strength of Masonry		✓	✓	IT 3	Material extraction and testing
			✓	IT 4, 5	In situ testing
Mortar Properties		✓	✓	IT 2	Petrography
			✓	IT 4, 5	In situ testing

NDE: Nondestructive

IT: Intrusive

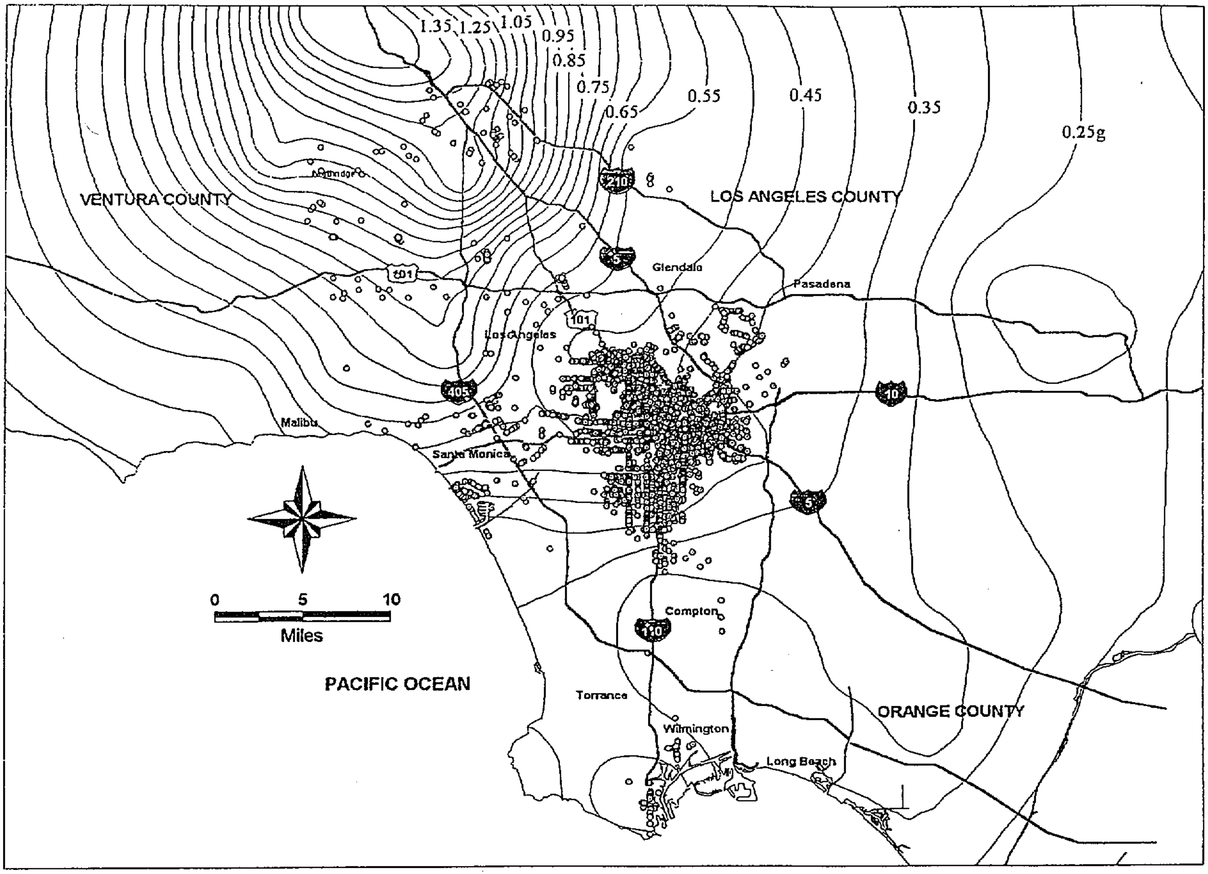


Figure 3-3 ***Spectral Acceleration Contours for T=0.3 sec., 1994 Northridge, California, Earthquake (from NIST, 1997, "dots" indicate locations of a particular building type)***

The procedures included in Section 3.8 are those that are generally accessible to the practicing engineering community and that have been used successfully on projects that required evaluation of existing concrete and masonry structures. They are not, however, an exhaustive list. Other more sophisticated or specialized techniques may be useful in specific instances.

The overall scope of the type and number of tests and inspections depends on a number of factors including:

- The completeness of existing documentation. If accurate and complete documentation of the structural conditions is available, the scope of the investigation may be relatively small.
- The nature and extent of the damage. Pervasive or diverse damage trigger more extensive investigations. Buildings with damage that may have occurred prior to the earthquake may require a greater degree of attention to distinguish between pre-existing conditions and earthquake damage.
- The quality of construction. If the field conditions differ routinely from construction documents, more investigative work will be required. If in-place material quality is inconsistent, more tests of individual components will be necessary.
- The correlation between analytical information and field observation. If calculations to identify critical components and expected damage give results that are corroborated by the actual damage, then fewer tests and inspections are warranted.

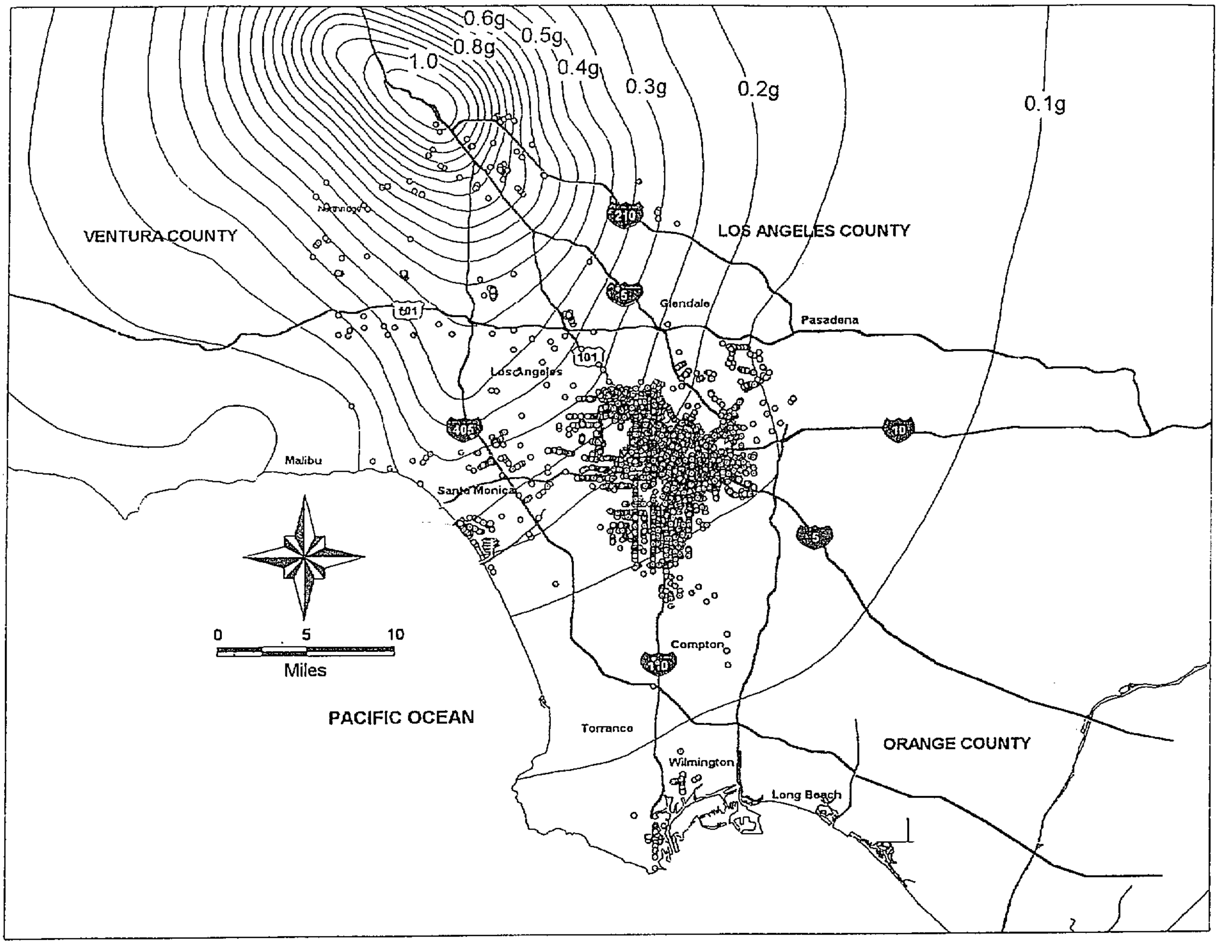


Figure 3-4 ***Spectral Acceleration Contours for T=1.0 sec., 1994 Northridge, California, Earthquake (from NIST, 1997, "dots" indicate locations of a particular building type)***

- The degree of accessibility to critical areas for visual examination.

In general, the scope of the investigation can vary considerably among individual buildings. A plan for the investigation should begin with relatively simple and inexpensive procedures. The goal should be to visually inspect all the elements and components of the lateral-load-resisting system. In some cases, finishes may prevent the examination of certain elements and components. If analysis suggests that damage is likely to have occurred in hidden areas, finishes should be removed for inspection at critical locations. As the investigation proceeds, the scope can be expanded, if necessary, based on the results of visual inspections and comparison with analytical predictions of behavior. When testing is needed to obtain material properties for a relative performance analysis, the number of tests required to quantify the in-place properties of the materials may be based on the guidelines provided in FEMA 273/274 and ATC-40.

3.4 Pre-existing Conditions

Interpretation of the findings of damage observations requires care and diligence. When evaluating damage to a concrete or masonry wall, an engineer should consider all possible causes in an effort to distinguish between that attributable to the damaging earthquake and that which occurred earlier (pre-existing conditions). ACI

224.1R (ACI Committee 224, 1994) discusses possible causes of cracking in reinforced concrete. Some of the causes described are also applicable to reinforced and unreinforced masonry construction. Since the evaluation of earthquake damaged buildings is typically conducted within weeks or months of the event, cracking and spalling caused by earthquakes is normally relatively recent damage. cracks associated with drying shrinkage or a previous earthquake, on the other hand, would be relatively old. General guidance for assessing the relative age of cracks based on visual observations is as follows.

Recent cracks typically have the following characteristics:

- Small, loose edge spalls
- Light, uniform color of concrete or mortar within crack
- Sharp, uneroded edges
- Little or no evidence of carbonation

Older cracks typically have the following characteristics:

- Paint or soot inside crack
- Water, corrosion, or other stains seeping from crack
- Previous, undisturbed patches over crack
- Rounded, eroded edges
- Deep carbonation

Evaluating the significance of damage requires an understanding of the structural behavior of the wall during the earthquake. The evaluating engineer must consider the implications of the observations with respect to the overall behavior of the building and the results of analytical calculations. The behavior must be correlated with the damage. If the observed damage is not reasonably consistent with the overall seismic behavior of the structure, the crack may have been caused by an action other than the earthquake.

3.5 Component Damage Classification

For each component of the structural system, the engineer classifies the damage according to behavior mode. Behavior mode indicates the predominant type of damage that a component sustains, or has the potential to sustain, in response to earthquake forces and displacements. The behavior mode depends on the relative strength of the component part for various actions (e.g., shear or moment). For each component, the engineer also classifies the severity of damage as follows:

Insignificant:	Damage does not significantly affect structural properties in spite of a minor loss of stiffness. Restoration measures are cosmetic unless the performance objective requires strict limits on nonstructural component damage in future events.
Slight:	Damage has a small effect on structural properties. Relatively minor structural restoration measures are required for restoration for most components and behavior modes.
Moderate:	Damage has an intermediate effect on structural properties. The scope of restoration measures depends on the component type and behavior mode. Measures may be relatively major in some cases.
Heavy:	Damage has a major effect on structural properties. The scope of restoration measures is generally extensive. Replacement or enhancement of some components may be required.
Extreme:	Damage has reduced structural performance to unreliable levels. The scope of restoration measures generally requires replacement or enhancement of components.

Chapters 5, 6, 7, and 8 address the classification of damage for components of reinforced concrete, reinforced masonry, unreinforced masonry, and infilled frames, respectively. Guidance is tabulated according to component type and behavior mode, to assist the engineer in identifying and for assessing the severity of the damage based on the observed conditions and calculations of component properties.

The information and guidance for each typical component type are summarized in tabular form in the Component Damage Classification Guides (Component Guides) at the end of each chapter. The intention is to provide practical assistance in a concise format for use by an engineer in applying the evaluation procedures. Component Guides are not intended to be used by inexperienced or unqualified observers of damage. The identification of components and the determination of modes of behavior requires a thorough understanding of the technical basis of the damage evaluation procedures.

The format of the Component Guides is similar for all components.

Behavior Mode

A brief summary of how to distinguish the particular behavior mode both by observation of the damage and by analysis is provided. These relate to damage inspection procedures (Sections 3.3 and 3.8) and the component evaluation techniques (Chapters 5, 6, 7, and 8).

Description of Damage

The central column in the tabular layout of the Component Guides contains descriptive information on the typical damage for the particular component. These data consist of sketches and verbal criteria relating the observed damage to the various damage severity classifications.

Severity

The left hand column of the Component Guides designates the severity of damage for the five categories described above in this Section. This column also contains the recommended component modification factors (λ - factors) for damaged components. These are used to change the basic properties of the components to reflect the effects of damage in a relative performance analysis (Section 4.4.3).

Performance Restoration Measures

The right hand column in the Component Guides tabulates performance restoration measures intended to restore, as much as possible, the structural properties of the component. In cases where complete restoration is not possible, component modification factors for the restored component (λ^*) are tabulated. The use of the performance restoration measures for damage evaluation is discussed in Section 4.5. The specific repair techniques are summarized in FEMA 308*: The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings.*

It is important to recognize that the Component Guides in Chapters 5, 6, 7, and 8 are representative of typically encountered conditions. Judgment is required to adapt and apply this information to specific conditions. The Component Guides were developed from a review of available empirical and theoretical data. Included with the Component Guides for each material is guidance on their use and the evaluation of component behavior. FEMA 307 provides additional technical background information and identifies resources for component identification and damage classification.

3.6 Verification

In practice, the investigation of damage and identification of components may be an iterative process. As presented in Chapter 2, the initial identification of components is based on relative strength and stiffness, and the anticipated inelastic lateral mechanism. Information from the field helps the engineer verify the component type based on actual behavior. For example, Figure 3-5 illustrates two possible inelastic lateral mechanisms for the same element. Theoretical calculations may predict one mechanism and therefore certain types of component damage. Observations of damage in the field, however, may lead to a different conclusion regarding the basic mechanism and component identification. There are several sources of discrepancies between analysis and observation, described below.

1. The distribution of the lateral forces from the damaging earthquake might have differed from that used in the analysis to generate the inelastic lateral mechanism. In such a case, the component behavior modes observed in the field might differ from those predicted analytically because of the relative magnitudes of component actions. For example, the use of a conventional upper triangular distribution of lateral load for a cantilevered shear wall might predict a flexural behavior mode in which the ultimate moment capacity at the base of the wall is attained before reaching the shear capacity. If a shearing behavior mode is encountered in the field, it may indicate a more rectangular or trapezoidal lateral

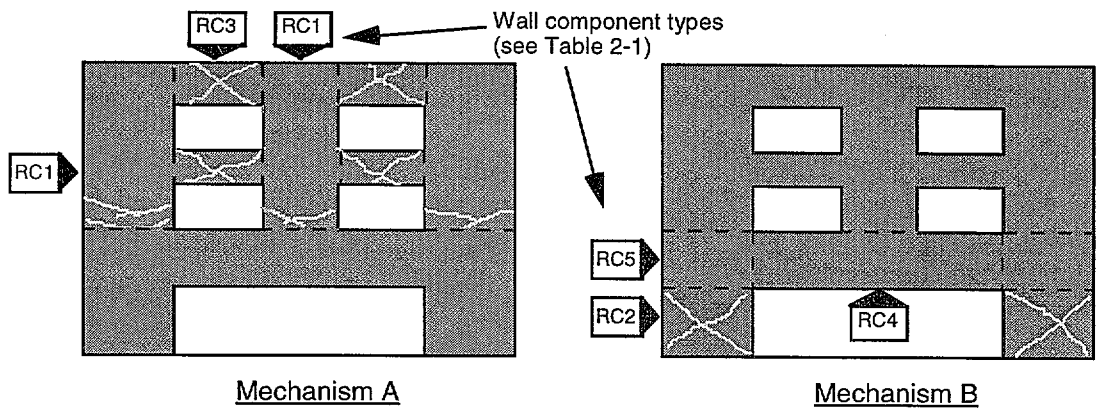


Figure 3-5 ***Different Inelastic Lateral Mechanisms and Components for Same Wall Element***

load distribution, which would tend to lower the shear span *(M/V)* for the component. Also, a uniform distribution of seismic forces is more likely to cause a story mechanism than an inverted triangular distribution

2. The strength of components for various actions may differ from that predicted analytically. This could lead to different component types and/or behavior modes being a better representation of actual behavior. Many of the conventional theoretical formulations for component strength are intended for use as design equations. As such, they reflect an appropriate degree of conservatism and are suitable for a wide range of applications. The damage evaluation process differs fundamentally from design. The objective is to use theory and observation to assess the actual strength and behavior of the structural components. Figure 3-6 illustrates the difference between design strength and expected strength for a flexural component. The component data in FEMA 307 provide resources for alternative formulations based on available empirical and theoretical research on actual behavior and material properties. If an alternative strength estimate correlates more closely with observed behavior and specific conditions, it is appropriate to use that estimate for evaluation purposes. This is not to imply that the estimate is then applicable for general design purposes.

3. The severity and significance of damage depends heavily on ductility and behavior mode (see Figure 3-7). Some components exhibit mixed behavior modes, as shown in the moderate-ductility example in Figure 3-7(b). The component initially exhibits flexural behavior, but there is a transition to shear-controlled behavior at higher deformations. This type of behavior is not unusual, and it can be difficult to identify. Chapters 5 through 8 and FEMA 307 provide additional information and guidance on this point.

4. The overall intensity of the damaging ground motion might differ from that assumed in the analysis. The maximum global displacement that actually occurred during the earthquake, d_e, could be larger or smaller than that predicted. This would tend to produce a correspondingly greater or lesser overall severity of component damage. Component type and behavior mode would not be affected in the absence of other differences.

Resolution of these discrepancies entails adjustments to the analysis and the structural model so that the resulting component types, behavior modes, and severity of damage match the observed conditions. In some cases, the engineer may decide to conduct further tests or investigations to resolve conflicting data. Properly implemented, the process concludes with a reasonable and consistent representation of the governing behavior modes and the actual damage, as is necessary for an accurate understanding of the response of the structure to the damaging ground motion.

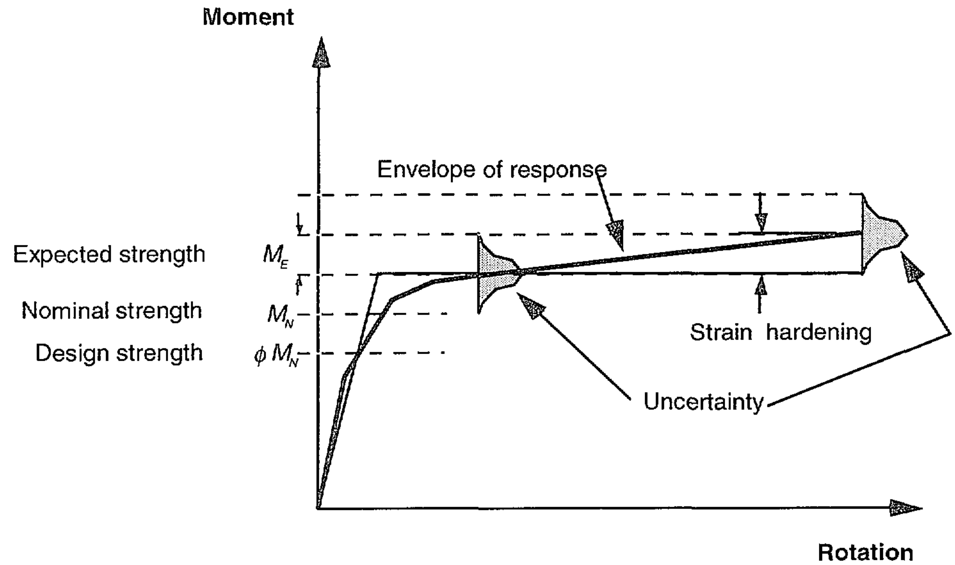


Figure 3-6 ***Relationship between design strength and expected strength***

3.7 Documentation

Documentation of the results of the investigation should be complete and unambiguous. Plan drawings should show the location of elements and components and the locations and dates of tests. Elevations of critical elements and components should also be included where appropriate. Test results should be tabulated in accordance with the recommendations in the guides.

Crack maps, sketches, and photographs, keyed to the plan drawings, should record all visual observations. Results of the investigation should be organized to focus on structural components and behavior modes. This organization facilitates the generation of Component Damage Record forms, shown in Figure 3-8.

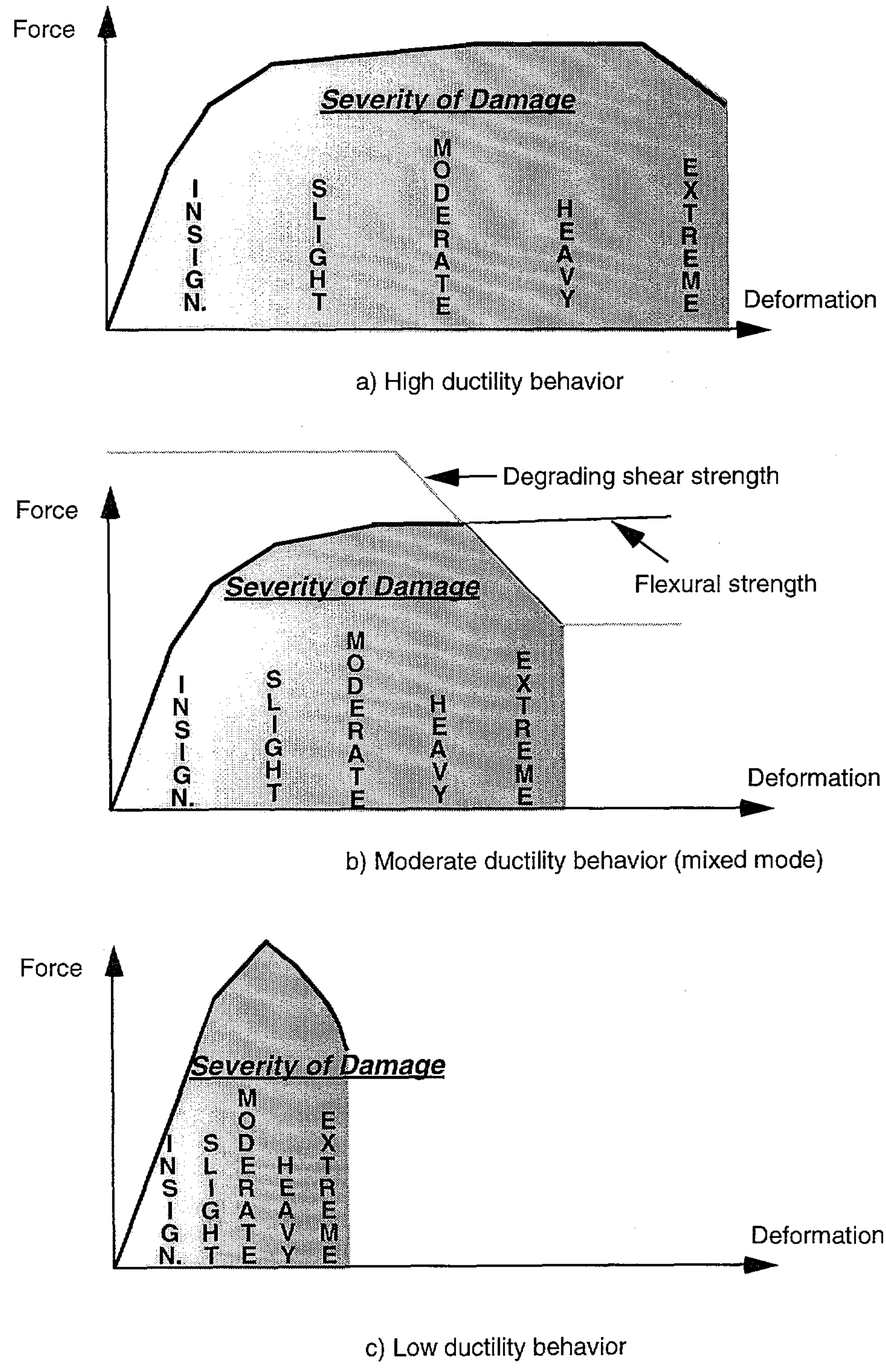


Figure 3-7 ***Component force-deformation behavior, ductility, and severity of damage***

<table>
<tr><td colspan="3"><u>Component Damage Record</u></td></tr>
<tr><td>Component ID:</td><td>Component Type:</td><td>Location:</td></tr>
<tr><td colspan="3">Sketch and description of damage types and severities (attach supplemental data if necessary):</td></tr>
<tr><td colspan="3">Test results summary (attach detail):</td></tr>
<tr><td>Building:</td><td>Engineer:</td><td>Inspection date:</td></tr>
<tr><td colspan="2">FEMA 306: Evaluation and Repair of Earthquake Damaged Concrete and Masonry Wall Buildings</td><td></td></tr>
</table>

Figure 3-8 *Example Component Damage Record*

3.8 Test and Inspection Guides

This section provides guidelines for the use of typical tests and inspections to assess the consequences of earthquake damage to concrete and masonry wall buildings as discussed in Section 3.3.

NDE 1	TEST AND INVESTIGATION GUIDE	Test Type:	**Nondestructive**
	VISUAL INSPECTION	Materials:	**Concrete, Reinforced Masonry, Unreinforced Masonry**

Description

Visual inspection is perhaps the most useful test available in the assessment of earthquake damage to concrete and masonry walls. Generally, earthquake damage to concrete and masonry walls is visible on the exposed surface. Observable types of damage include cracks, spalls and delaminations, permanent lateral displacement, and buckling or fracture of reinforcement. Visual inspection can also be useful for estimating the drift experienced by the building.

Visual inspection should always accompany other testing methods that are used. Findings from the visual inspections should be used as a basis for determining locations for conducting further testing. The observed damage should be documented on sketches. The patterns of damage can then be interpreted to assess the behavior of the wall during the earthquake.

Equipment

The materials and equipment typically required for a visual inspection are a tape measure, a flashlight, a crack comparator, a pencil, and a sketchpad.

A tape measure is used to measure the dimensions of the wall and, if necessary, to measure the lengths of the cracks. Tape measures that are readily available from a hardware store, with lengths of 20 to 50 feet, are sufficiently accurate for damage evaluation.

Flashlights are used to aid in lighting the areas to be inspected. In postearthquake evaluations, electric power may not be completely available, so supplemental lighting should be supplied.

In a visual inspection, the engineer uses a crack comparator or a tape measure to measure the width of cracks at representative locations. Two types of crack comparators are generally available: thin clear plastic cards, which have specified widths denoted on the card and small, hand-held magnifying lenses with a scale marked on the surface. Plastic card comparators have gradated lines to a minimum width of about 0.002 inches. Magnifying lens comparators are accurate to about 0.001 inch (ACI Committee 201, 1994a).

The engineer uses a sketchpad to prepare a representation of the wall elevation, indicating the locations of the cracks, spalling, or other damage. All significant features of the wall should be recorded, including the dimensions of openings, the finishes on the wall, and the presence of nonstructural elements that may affect the repairs. The sketch should be supplemented with photographs or video tape.

Detailed examination of the surface of a crack can be accomplished with a portable microscope, which allows for magnified viewing of the surface of the cracks. Portable microscopes are available with magnifications of 18- to 36-fold. An external light source is needed for viewing. A camera adapter may be available for photographic documentation.

TEST AND INVESTIGATION GUIDE
continued

NDE 1

Execution

The initial steps in the visual observation of earthquake damage are to identify the location of the wall in the building and to determine the dimensions of the wall (height, length, and thickness). A tape measure is used for quantifying the overall dimensions of the wall. A sketch of the wall elevation should then be prepared. The sketch should include sufficient detail to depict the dimensions of the wall, it should be roughly to scale, and it should be marked with the wall location (See example on page 33).

Observable damage such as cracks, spalling, and exposed reinforcing bars should be indicated on the sketch. Sketches should be made in sufficient detail to indicate the approximate orientation and width of cracks. Crack width is measured using the crack comparator or tape measure at representative locations along significant cracks. Avoid holes and edge spalls when measuring crack widths. Crack widths typically do not change abruptly over the length of a crack. If the wall is accessible from both sides, the opposite side of the wall should be checked to evaluate whether the cracks extend through the thickness of the wall and to verify that the crack widths are consistent.

Photographs can be used to supplement the sketches. If the cracks are small, they may not show up in the photographs, except in extreme close-up shots. Paint, markers, or chalk can be used to highlight the location of cracks in photographs. However, photographs with highlighted crack should always be presented with a written disclaimer that the cracks have been highlighted and that the size of the cracks cannot be inferred from the photograph.

During a visual inspection, the engineer should carefully examine the wall for the type of damage and possible causes. ACI 201 is a guide that describes conditions that might be observed when surveying concrete walls. Indications that the cracks or spalls may be recent or that the damage may have occurred prior to the earthquake should be noted. The guidelines in Section 3.4 can be helpful for assessing the relative age of the cracks.

Visual observation of the nonstructural elements in the building can also be very useful in assessing the overall severity of the earthquake, the interstory displacements experienced by the building, and the story accelerations. Full-height nonstructural items such as partitions and facades should be inspected for evidence of interstory movement such as recent scrapes, cracked windows, or crushed wallboard.

Personnel Qualifications

Visual inspection of concrete and masonry walls should be performed by an engineer or trained technician. Engineers and technicians should have previous experience in identifying damage to concrete and masonry structures and should be familiar with the use of a tape measure and crack comparator. Engineers and technicians should also have sufficient training to be able to distinguish between recent damage and damage that may have been pre-existing. For this type of assessment, the person conducting the inspection should understand how the structure is designed and how earthquake, gravity, and other forces may have acted on the wall.

TEST AND INVESTIGATION GUIDE

continued

NDE 1

Limitations

The width of a crack can vary substantially along its length. Both the plastic card and the magnifying crack comparators can produce a reasonable estimate of the width of a crack. The magnifying comparators are generally more accurate when measuring small (<0.001 inches) crack widths. The plastic cards can sometimes overestimate the crack width due to the lighting conditions. With either type of comparator, the crack width is only measured at representative locations to determine repair thresholds. The measurements should be used primarily to compare damage levels among walls. The crack comparators may not be necessary when the crack widths are to be measured in 1/16-inch increments. For wider cracks, a tape measure will provide sufficiently accurate values.

Visual observation of concrete and masonry walls can generally identify most of the earthquake damage to those elements. In some cases, the presence of finishes on the walls can prevent an accurate assessment of the damage. Brittle finishes such as plaster can indicate damage that may not be present in the underlying substrate. Soft finishes such as partitions isolated from the structural walls can obscure minor amounts of damage.

References

ACI Committee 201, 1994a, "Guide for Making a Condition Survey of Concrete in Service", ACI 201.1R-92, *Manual of Concrete Practice*, American Concrete Institute, Detroit, Michigan.

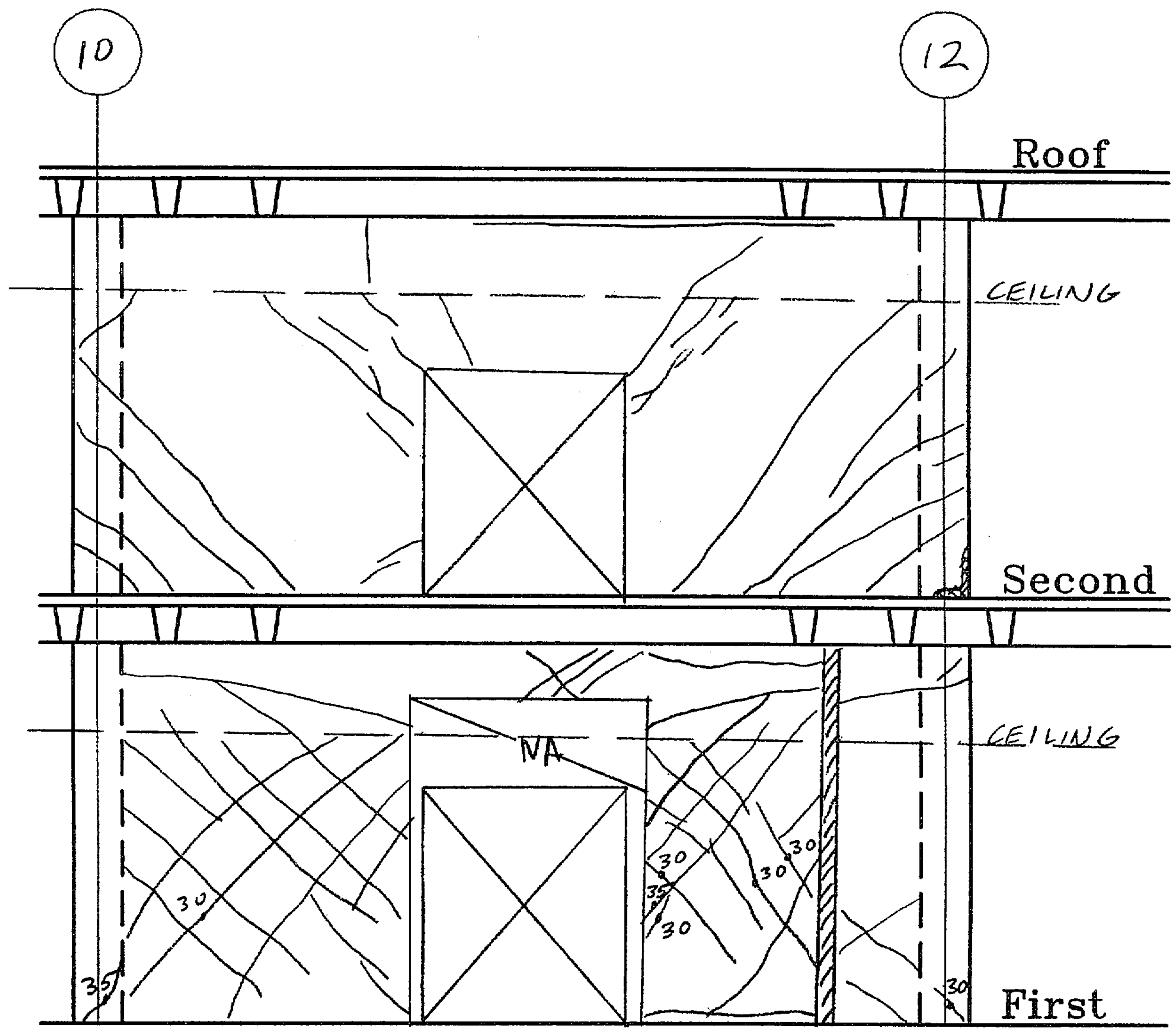
ACI Committee 224, 1994b, Causes, Evaluation and Repair of Cracks in Concrete Structures", ACI Committee 224.1R-93, *Manual of Concrete Practice*, American Concrete Institute, Detroit, Michigan.

ACI Committee 364, 1994c, "Evaluation of Structures Prior to Rehabilitation", ACI 364.1R, *ACI Manual of Concrete Practice*, American Concrete Institute, Detroit, Michigan.

Component Damage Record (Example)

Building Name: Concrete Shear Wall Building	Project ID: ATC 43 Example	Prepared by: ATC
Location Within Building: Floor: $1^{st}/2^{nd}$ Column Line: B Component Type:		Date: 24-Sep-97

Sketch and Description of Damage:



Legend:

- Crack
- 30 — Crack Width in Mils (0.001 Inch)
- Crack Previously Filled with Epoxy
- Crack at Pre-existing Surface Patch
- Spall
- NA — Not Accessible
- Partition

TEST AND INVESTIGATION GUIDE	Test Type:	**Nondestructive**
NDE 2 — SOUNDING	Materials:	**Concrete, Reinforced Masonry**

Description

Tapping on a wall with a dense object, such as a hammer, and listening to the vibrations emitted from the wall can be useful for identifying voids or delaminations in concrete walls. The sound produced from a solid wall will be different from that from a wall with voids or delaminations close to the surface. In concrete block masonry walls, sounding can be used to verify that the cells in the blocks have been grouted.

Equipment

The typical equipment required for sounding is a hammer. However, any hard, dense object can be used.

Execution

In areas where the visual observations indicate that the wall may have delaminations, the wall can be sounded by tapping with a hammer. Delaminations and spalls will generally produce a hollow sound (ACI, 1994) when compared with solid material. The wall should be tapped several times in the suspect area and away from the suspect area, and the sounds compared. It is important to test an area that is undamaged, and of the same material and thickness to use as a baseline comparison. For a valid comparison, the force exerted by the tapping should be similar for both the suspect and baseline areas.

In reinforced masonry construction, sounding can be used to assess whether the cells in the wall have been grouted. Near the ends of a block, the unit is solid for the full thickness of the wall. For most of the length of the block, it is relatively thin at the faces. If the sound near the end of the block is substantially different than at the middle of the cell, the cell is probably not grouted.

Personnel Qualifications

Sounding of concrete and masonry walls should be performed by an engineer or trained technician. Engineers and technicians should have previous experience in identifying damage to concrete and masonry structures. Engineers and technicians should also be able to distinguish between sounds emitted from a hammer strike. Prior experience is necessary for proper interpretation of results.

Reporting Requirements

The personnel conducting the tests should provide sketches of the wall indicating the location of the tests and the findings. The sketch should include the following information:

- Mark the location of the test on either a floor plan or wall elevation.
- Report the results of the test, indicating the extent of delamination.
- Report the date of the test.
- List the responsible engineer overseeing the test and the name of the company conducting the test.